Product Environmental Life-Cycle Assessment Using Input-Output Techniques

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Summary

Life-cycle assessment (LCA) facilitates a systems view in environmental evaluation of products, materials, and processes. Life-cycle assessment attempts to quantify environmental burdens over the entire life-cycle of a product from raw material extraction, manufacturing, and use to ultimate disposal. However, current methods for LCA suffer from problems of subjective boundary definition, inflexibility, high cost, data confidentiality, and aggregation.

This paper proposes alternative models to conduct quick, cost effective, and yet comprehensive life-cycle assessments. The core of the analytical model consists of the 498 sector economic input-output tables for the U.S. economy augmented with various sector-level environmental impact vectors. The environmental impacts covered include global warming, acidification, energy use, non-renewable ores consumption, eutrophication, conventional pollutant emissions and toxic releases to the environment. Alternative models are proposed for environmental assessment of individual products, processes, and life-cycle stages by selective disaggregation of aggregate input-output data or by creation of hypothetical new commodity sectors. To demonstrate the method, a case study comparing the life-cycle environmental performance of steel and plastic automobile fuel tank systems is presented.

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Introduction

Environmentally conscious decision making requires information about environmental consequences of alternative products, processes or activities. Life-cycle assessment (LCA) is a systematic tool to analyze and assess environmental impacts over the entire life cycle of product. LCA involves tracing out the major stages and processes involved over the life cycle of a product covering: raw materials extraction, manufacturing, product use, recycling and final disposal, identifying and quantifying the environmental impacts at each stage. The goal of LCA is to facilitate a systems view in product and process evaluation (Lave et al. 1995; Miettinen and Hamalainen 1997; Keoleian and Menerery 1993).

The LCA approach is widely recognized as a useful framework and attempts are underway to integrate life-cycle thinking into business decisions. A major international initiative in this direction is the series of environmental management standards (EMS) proposed by the International Standards Organization, widely known as ISO 14000. Standards being developed for inclusion under ISO 14000 include principles and guidelines for conducting LCA for product evaluation (Tibor and Feldman 1996). Similarly, the document "Guidance on acquisition of environmentally preferable products and services," prepared by the United States Environmental Protection Agency (U.S. EPA) to help implement the President's Executive order 12873, recommends LCA approach in all federal procurement (U.S. EPA 1995c; Vigon et al. 1993). Many eco-labeling and product take back regulations in Europe require life-cycle environmental analysis of products (Davis 1993).

Although conceptually simple and appealing, LCAs are difficult to carry out in reality. Production of most typical products and materials requires a large number of diverse inputs, which in turn use many other inputs in their production. Often there are interdependencies in inputs, which have to be modeled. Attempting to trace all the direct and indirect inputs and associated environmental burdens all the way to ultimate raw material extraction becomes an unwieldy exercise. For example, steel making requires a large number of inputs including iron ore, limestone, coke, electricity, chemicals, alloys, railroad services, computer support, and so on, which in turn draw on resources from almost all sectors of the economy, including the steel industry. In order to keep the analysis tractable, most LCAs limit the scope of analysis only to the major inputs at each stage, leading to problems of subjective boundary definition and comparability across studies. Moreover, data on input requirements and emissions for even such truncated LCAs have to be collected from a large number of different suppliers leading to high cost, time, and issues of data confidentiality and verifiability. As a result, LCA is considered a flawed tool that cannot deliver what it promises (Portney 1993; Arnold 1993; Lave et al. 1995).

To address the problem of subjective boundary definition in conventional LCA, Lave and colleagues proposed using economic input-output analysis techniques in LCA (Lave et al. 1995). Economic input-output life-cycle assessment (EIO-LCA) takes a top-down approach and treats the whole economy as the boundary of analysis. Another strength of EIO-LCA approach is that economy-wide interdependencies in inputs are modeled as a set of linear simultaneous equations. Although less common and limited in scope, the representation of input interdependencies as systems of equations can be found elsewhere in the LCA literature. For example, Pento constructs input-output matrices for the paper industry in his dynamic life-cycle inventory modeling (Pento 1997). Similarly, the commercially available KCL-ECO LCA program represents product life-cycle inventory as a set of linear equations of physical quantities (Karna and Engstrom 1994).

Lave and colleagues implement their economic input-output life-cycle assessment (EIO-LCA) model using 498 × 498 commodity sector direct requirements matrix published by the U.S. Department of Commerce as a part of the 1987 U.S. input-output tables (U.S. Commerce 1994). They augment the direct requirements matrix with sector-level toxic release emission factors and electricity use intensity. They approximate the product, whose LCA is required, by the corresponding commodity sector. For example, in comparing the life-cycle environmental burdens of paper cups and plastic cups, they approximate paper cups by the industry sector "Paperboard Containers and Boxes" and plastic cups by the industry sector "Plastic Materials and Resins." The life-cycle toxic emissions and electricity use from paper cup and plastic cup production are approximated by economy-wide impacts to meet a given incremental final demand of the corresponding commodity sectors.

EIO-LCA, as proposed, leads to a consistent boundary definition. However, it is still subject to several well-recognized limitations (Lave et al. 1995). First, the product of interest is approximated by its commodity sector in the national input-output tables with respect to input requirements and environmental coefficients. But the commodity sectors in the national input-output tables are broad aggregates that include a large number of products. As a result, current EIO-LCA is appropriate for comparing aggregate, disparate products that are well approximated by their commodity sectors, but not for comparing heterogeneous products within a commodity sector, or products that differ significantly from representative output of the sector, or completely new products. Second, EIO-LCA captures the upstream environmental burdens associated with raw materials acquisition and manufacturing stages, but not those associated with product use and end-of-life options.

This paper extends the EIO-LCA approach to provide a flexible tool for comprehensive LCA of products. The core of the analytical model continues to be the 498 commodity sector direct requirements matrix for the U.S. economy augmented with various sector-level environmental impact vectors. The environmental impacts covered are significantly expanded to include global warming, acidification, energy use, non-renewable ores consumption, eutrophication, and conventional pollutant emissions. Alternative models are proposed for environmental assessment of individual products, processes, and life-cycle stages by selective disaggregation of aggregate input-output data or by creation of hypothetical new commodity sectors. To demonstrate the method, a case study comparing the life-cycle environmental performance of steel and plastic automobile fuel tank systems is presented.

The remainder of the paper is organized as follows: in the next section I describe the mathematical structure of the basic EIO-LCA. I then present alternative models for conducting LCA of individual products; the development of various environmental impact matrices; an illustrative case study comparing steel and plastic automobile fuel tank systems, followed by conclusions and discussion.

Mathematical Structure of Economic Input-Output Life-Cycle Assessment

Input-output analysis is a well-established tool in economic analysis, where the interdependencies across different sectors of the economy are represented by a set of linear equations. The core of the model is the inter-sectoral direct requirements (or technical coefficients) matrix denoted as **a**. An element a_{ij} of matrix **a** represents the dollar value of input required from sector i to produce one dollar worth output of sector j ($i = 1...n$, and $j = 1...n$). Let **x** represent the vector of total outputs of the sectors. The exogenous change in final demand for the output of these sectors is represented by a vector **f**. (For a more detailed description of input-output analysis, underlying assumptions about the structure of the economy and limitations, refer to the work of Leontief (1966), Miller and Blair (1985), Hendrickson and colleagues (1998); and the U.S. Department of Commerce (U.S. Commerce 1994).

Because the total output of a sector is the sum of final demand **f** and intermediate demand **ax**, (i.e. demand as input requirement for producing the output of other sectors), the input-output system can be written:

$$\mathbf{x} - \mathbf{ax} = \mathrm{f} \tag{1}$$

The vector of sectoral outputs to meet a given exogenous demand **f** is obtained by premultiplying (1) by $[\mathbf{I} - \mathbf{a}]^{-1}$

$$\mathbf{x} = [\mathbf{I} - \mathbf{a}]^{-1}\,\mathbf{f} \tag{2}$$

The input-output technique can be extended for environmental analysis.[1] Suppose **r** is a $k \times n$ matrix of environmental burden coefficients, where r_{kj} is environmental burden k (e.g. carbon monoxide emissions) per dollar output of sector j; and **e** is the vector of total environmental burdens, then the economy-wide total (direct and indirect) environmental burden associated with an exogenous demand vector **f** becomes

$$\mathbf{e} = \mathbf{r}\mathbf{x} = \mathbf{r}\,[\mathbf{I} - \mathbf{a}]^{-1}\mathbf{f} \qquad (3)$$

The environmental burden matrix **r** can include coefficient vectors for any environmental impact of interest such as energy use, non-renewable resource use, greenhouse gas emissions, etc. The contribution of individual industry sectors to the total environmental burden can be found by replacing each of the environmental burden coefficient vectors in **r**, by its diagonal matrix.

In theory, one can develop very large technical coefficient and environmental burden matrices representing all possible products as separate commodity sectors, and then use equation (3) to estimate economy-wide burdens to meet an incremental demand for any product. However, this approach is not practical in view of the immense data requirements. The largest available technical coefficient matrix, published by the U.S. Department of Commerce, has 498 commodity sectors (U.S. Commerce 1994).

Models of Economic Input-Output Life-Cycle Analysis of Products

Equation (3) gives the direct and indirect environmental burden associated with an exogenous change in the demand for the output of the sector as a whole. However, a typical product LCA involves estimation of environmental burden associated with an exogenous increase in the demand of a specific product, which might be different from the average output of an industrial sector with respect to both technical and environmental discharge coefficients, or a completely new product/design. I present several alternative models, in order of increasing degree of comprehensiveness, complexity, and data intensity for carrying out such product LCA.

Model I: Approximating the Product by its Sector

This is the simplest model in which the product of interest is assumed to be well approximated by its industry sector, with respect to both technical and environmental burden coefficients. (Approximation used in Lave et al. 1995; Cobas-Flores 1996; Horvath 1997). Direct and indirect effects of incremental output of a particular product can then be estimated by treating it as a change in exogenous demand for the output of the sector. The implicit assumption here is that input requirements and environmental burdens are proportional to product price. This approach is simple, quick, and does not require any additional data. It provides useful information, especially when comparing broad industry sectors, or typical outputs of industry sectors. It is also useful as an initial screening device to prioritize further data collection efforts.

Model II: Product as a New Hypothetical Industry Sector

Often, it is necessary to conduct an LCA of an existing product that is not a representative output of its commodity sector, or a completely new product. If information on the inputs that are required to produce the product, and direct environmental burdens from the production process are available, then the product of interest can be represented as a new hypothetical sector entering into the economy. The economy-wide environmental burdens arising from a unit output of the new industry sector can then be estimated.

Let $\mathbf{a} = [a_{ij}]$ $i, j = \{1, 2.....n\}$ be the current aggregate technical coefficient matrix of the economy with n sectors. Assume the product is represented as sector $n+1$. Let $a_{i,n+1}$ be dollar value of input required from sector i $\{i=1...n+1\}$ to produce a dollar worth of the product. Further assume that the inputs used in its production are representative output of the sectors from which they are drawn. Let $[\,\mathbf{r}_{n+1}]$ be the column vector of environmental burdens associated with a dollar worth output of sector $n+1$.

Define a new technical coefficient matrix **A**, where the first n row and column elements remain unchanged from **a**,

$$\boldsymbol{A} = \left[\begin{array}{c:c} \mathbf{a} & \mathbf{a}_{i\,n+1} \\ \hdashline 0 & \mathrm{a}_{\,n+1} \end{array}\right]$$

Similarly, the new environmental burden matrix is reformulated as:

$$\mathbf{R} = [\, r_1 \,.....\, r_n \quad r_{n+1}\,]$$

The economy-wide environmental burden **E** associated with an output f_{n+1} of the new sector $n+1$ is

$$E = RX = R [I - A]^{-1} F \qquad (4)$$

where $F^t = [0,.....0, f_{n+1}]$

Alternatively, one can consider that output of the product results in exogenous increases in the demand for its input requirements in the economy, i.e. the changes in exogenous demand vector f_1 is equal to the input requirement vector for producing f_{n+1} dollars worth of output of the product. The total environmental burden associated with the product is then the sum of environmental burden associated with the production of its input requirements and the direct environmental burden associated with its production, $f_{n+1} \times r_{n+1}$. (This is the "final demand approach" outlined by Miller and Blair (1985)).

$$\mathbf{E} = \mathbf{r} [\mathbf{I} - \mathbf{a}]^{-1} \mathbf{f}_1 + f_{n+1} \times \mathbf{r}_{n+1} \qquad (5)$$

Equations (4) and (5) are equivalent.

Model III: Disaggregating an Existing Industry Sector

The underlying assumption in Model II is that the original technical coefficient matrix is unaffected by the introduction of the new sector. However, this may not always be the case, because most products of interest are already included in existing commodity sectors and often used as intermediate inputs in other sectors. Suppose that the total environmental burden associated with exogenous changes in demand for a product, which is already included in one of the existing sectors, needs to be estimated. The sector, say sector *n*, which includes the product of interest can be disaggregated into two sectors, one of which is the product of our interest (sector n+1) and the other sector consisting of all other products within the sector. For example, for conducting LCA of paper cups, the sector "Paperboard Containers and Boxes" can be disaggregated into two sectors, "Paper Cups" and "All Other Products in Paperboard Containers and Boxes Except Paper Cups." It means a new $n+1 \times n+1$ technical coefficient matrix **A** , with elements A_{ij} has to be derived to represent the same economy represented by $n \times n$ matrix **a** (with elements a_{ij}).

The first $n - 1$ sectors of **a** and **A** are identical because the original sector *n* in **a** is a linear aggregation of sectors *n* and $n+1$ in **A** ,

$$a_{in} = (1 - s)\, A_{in} + s\, A_{i\,n+1} \qquad (6)$$

where *s* is the share of product $n+1$ in the total output of original aggregate sector *n*.

Similarly, the purchases of sector *j* from aggregate sector *n* in ***a*** is the sum of purchases from disaggregated sectors *n* and $n+1$ *in* **A**, i.e.

$$a_{nj} = A_{nj} + A_{n+1\,j} \qquad (7)$$

Also

$$\begin{aligned} a_{nn} = {} & (1 - s)(A_{nn} + A_{n+1\,n}) \\ & + s(A_{n\,n+1} + A_{n+1\,n+1}) \end{aligned} \qquad (8)$$

Equations (6) to (8) are the constraints on the coefficients of **A** such that aggregation of sectors *n* and $n+1$ in **A** yields **a**. **A** has a total of $4n$ unknown coefficients. However, because there are $2n - 1$ constraints on these coefficients, data on only $2n + 1$ coefficients is required. The share *s* of the product of our interest in the aggregate output of the original sector *n* can easily be obtained from secondary sources. The technical coefficient vector $[\mathbf{A}_{i,n+1}]$ for the product of interest can be estimated from a detailed cost sheet of the product, because the element $A_{i,n+1}$ is dollars worth of inputs from sector *i* required to produce a dollar worth of the product $n+1$. Data on the sales of product $n+1$ to different existing sectors *j* of the economy is required to estimate coefficients $A_{n+1,j}$. The firms manufacturing the product typically have information on the markets and market shares for its products.

Similarly if $\mathbf{r} = [r_1.....r_n]$, the environmental burden matrix associated with the original matrix is available, only data on the direct environmental burden vector $\boldsymbol{R}_{n+1}$ associated with the product $n+1$ is needed, to obtain the disaggregated environmental burden matrix **R,** because:

$$r_n = (1 - s)\, R_n + sR_{n+1} \qquad (9)$$

Once the disaggregated matrices **A** and **R** are developed, the total environmental burden associated with exogenous changes in the demand for the product (i.e. output of sector $n+1$) can be obtained from equation (4).

Model IV: Iterative Disaggregation, When a Limited Conventional LCA Is Available

The approach outlined in Model III can easily be extended and generalized when more detailed information on more than one stage of the upstream inputs is available, typically in the form of a conventional LCA. An expanded technical coefficient matrix **A** and environmental burden matrix **R** can be developed by iterative disaggregation of relevant sectors and creating additional industry sectors corresponding to each product or input for which detailed information is available.

To continue with the paper cup example, suppose a conventional LCA process model provides detailed information on the inputs and environmental burdens from the paper cup production process and production of wax paper used in paper cup manufacture. Based on this information, the sector "Paperboard Containers and Boxes" can be disaggregated into "Paper Cups" and "Others Except Paper Cups" sectors, and the sector "Paperboard and Paper Mills" can be disaggregated into "Wax Paper" and "All Other Paper Mill Products Except Wax Paper" sectors. The other inputs for which detailed process models are not available can be approximated by their corresponding commodity sectors (which typically are excluded in a conventional LCA).

To present a general case, suppose **a** (with elements a_{ij}) is the aggregate matrix, and a disaggregated matrix **A** (with elements A_{ij}^{kl}), where each of the aggregate sectors has been disaggregated into k subsectors (k may vary for each sector) is needed. Let s_i^k be the share of output of the kth subsector in the total output of aggregate sector i. Similarly let $\mathbf{r}_i^k$ be the environmental burden vector associated with a dollar output of kth subsector of aggregate sector i.

Along the lines of constraints (6) to (9), following are the constraints on the elements of **A**.

$$\sum_k s_i^k = 1 \tag{10}$$

$$a_{ij} = \sum_k s_i^k A_{ij}^{kl} \tag{11}$$

$$a_{ij} = \sum_l A_{ij}^{kl} \tag{12}$$

$$r_i = \sum_k s_i^k R_i^k \tag{13}$$

The information on input requirements and direct environmental burdens from the manufacturing process of intermediate inputs available in the conventional LCA is incorporated as in Model III to derive the larger disaggregated matrix. The expanded technical coefficient matrix and environmental burden matrices can then be used to estimate the total environmental burden associated with an increase in exogenous demand for the product/industry sector of interest.

In essence, this approach incorporates all the detailed information available, approximates missing information, and at the same time maintains the whole economy as the boundary of analysis.

Model V: Inclusion of the Use Phase of Product Life-Cycle Assessment

Alternative designs of durable goods such as automobiles, home heating devices, and washing machines may differ not only in the environmental burdens in the manufacturing stage, but also in resource consumption and environmental impacts in the use phase of their life-cycle. With some simplifying assumptions, the above models, especially Model II, can be used to estimate direct and indirect resource use and environmental burdens from the product use phase. The use phase can be treated as a hypothetical industry sector that draws inputs from the existing sectors and has some associated environmental burdens. The life-cycle burdens associated with all the inputs in the use phase can be estimated by economy-wide impacts for a given output of the hypothetical industry sector. The underlying strong assumption in this approach is that the technical coefficients matrix for the economy remains unchanged during the lifetime of the product and the time discount rate for environmental burdens is zero. This might be a good approximation when products have short life spans. Even when the products have longer life spans, this approach provides a good starting point by providing comparative information under the current state of the technology.

Model VI: Inclusion of End-of-Life Management Options

The product EIO-LCA approach can be extended to analyze life-cycle environmental burdens from management options at the end of the useful life of a product, such as reuse, remanufacturing, recycling, or disposal. End-of-life (EoL) management options, such as recycling, use inputs from existing industry sectors to process an obsolete product and produce an output which is demanded either for final consumption or as an intermediate input by other sectors. Typically remanufactured products are used by the same industry sector as substitutes for new components, while recycled output may be demanded by completely different sectors. Hence, these options can be conceptually treated as additional hypothetical industry sectors in EIO-LCA.

The net environmental impact from EoL management is the sum of life-cycle burdens from inputs used in EOLM, direct impacts from EOLM process itself, and credits for the recycled product. For example, the net environmental impact from recycling aluminum beverage cans is the sum of: life-cycle environmental burdens from all the inputs used in collecting and processing the cans, environmental burdens from the aluminum recovery process itself, and the credits for the recycled aluminum. When a recovered product can substitute the output of an existing industry sector, the environmental credit for recovered product is the avoided life-cycle environmental burdens from this substitution. For example, if a ton of aluminum scrap recycling results in the recovery of 0.6 MT of aluminum valued at $500, then the appropriate credit for recovered aluminum is the avoided economy-wide burdens from a reduction of $500 in the final demand for the output of the primary aluminum sector. When the recovery process results in many products, or the recovered products are likely to be used by many other industry sectors, new industry sectors representing the EOLM options can be added to the input-output matrix. Appropriate adjustments can be made for the technical and environmental coefficients for the existing industry sectors. However, in using this approach, the temporal effects of the useful life of the product are once again assumed away.

The above models show how the EIO-LCA framework can be extended to conduct LCAs of individual products and life-cycle stages. The models also show how more product-specific data available in a conventional LCA can be integrated with EIO-LCA, thus overcoming problems of subjective boundary definition in conventional LCA and aggregation problems in EIO-LCA. Further, these models are flexible. Depending on the data and cost constraints, LCAs of different levels of complexity and accuracy can be conducted while consistently maintaining the boundary of analysis as the whole economy with all its associated interdependencies.

Development of Comprehensive Environmental Impact Matrices

We augment the 498 × 498 commodity by commodity direct requirements (or technical coefficients) matrix of the U.S. economy for the year 1987, with estimates of various environmental burdens/dollar output of each commodity sector. Only publicly available data sources are used, which have advantages of large sample size, transparency of methods, verifiability, and periodic updating by public agencies. The general impact themes covered include:

- energy use,
- non-renewable ores use,
- conventional pollutant emissions,
- toxic releases,
- hazardous solid waste generation, and
- fertilizer use (as an indicator of the eutrophication potential).

Impacts from individual pollutant emissions are aggregated and summarized using appropriate weighting factors such as global warming potential, acidification potential, ozone depletion potential, and toxicity weighting factors. Similarly, total energy use is derived by aggregating the heating values of individual fuels.[2] The values of output of the six-digit U.S. input-output commodity (US-IO) sectors are from the benchmark input-output accounts for the U.S. economy, published by the U.S. Department of Commerce (U.S. Commerce 1994). The various data sources are summarized in table 1. More details on the estimation procedures, data sources, and limitations are available (Joshi 1998).

Fuel use and energy consumption: Data on purchases of different fuels by the six-digit US-IO sectors are from the work files used in preparation of the 1987 benchmark input-output accounts for

Table 1 Summary of environmental impacts included in EIO-LCA and data sources

Environmental impact area	*Data sources*
Energy Consumption	
Fossil Fuel Consumption	US-IO work files 1987 (U.S. Commerce 1994)
Electricity Consumption	U.S. Census of Manufactures 1987 (U.S. Commerce 1987)
Non-renewable Ore Consumption	US-IO work files 1987
Fertilizer Consumption (Eutrophication)	US-IO work files 1987
Toxic Chemical Releases	U.S. Toxic Release Inventory 1993 (U.S. EPA 1993b)
Toxicity Weighting Factors	Horvath et al. 1995
RCRA Hazardous Waste	US-RCRA database (Horvath 1997)
Conventional Pollutant Emissions from Fuel Use	US-IO work files, U.S. EPA 1995a, and IPCC 1995
Global Warming Potential	US-IO work files, IPCC 1995, USTRI 93 (U.S. EPA 1995b)
Acidification Potential	US-IO work files, U.S. EPA 1995b, Adriaanse 1993
Ozone Depletion Potential	USTRI 93 (U.S. EPA 1995b), Horvath 1997

the U.S. economy, available from the U.S. Department of Commerce (henceforth referred to as US-IO work files). These work files provide data on the value of purchases of about 7,000 commodities, including major fuels, by various industry sectors. The quantity estimates are based on average prices of individual fuels. The data on electricity use by the industry sectors are from the U.S. Census of Manufactures (U.S. Commerce 1987). The total energy consumption is calculated by summing the energy content of different fossil fuels and electricity from non-fossil sources.

Non-renewable ores use: Data on value of direct purchases of various ores by different industry sectors are available in the US-IO work files. The average producer price data for different ores from the Minerals Yearbook (USBM 1988) are used to estimate consumption intensities of ores by different industry sectors.

Toxic releases: The earlier EIO-LCA model developed by Lave and colleagues (Lave et al. 1995; Cobas-Flores 1996) included data on toxic chemical emission coefficients at sector level for over three hundred chemicals, estimated from U.S. EPA's Toxic Release Inventory (TRI) database (U.S. EPA 1995b). Horvath and colleagues (1995) proposed a toxicity weighting scheme for aggregating TRI chemicals called CMU-ET, wherein the time-weighted average threshold limit values of various chemicals relative to the threshold limit value of sulfuric acid are used as weights. The threshold limit value is the air concentration of the chemical that cannot be exceeded during any eight-hour work shift of a forty-hour work week, as per the occupational health guidelines of the American Conference of Governmental Industrial Hygienists (ACGIH). The CMU-ET weighting factors are included in this EIO-LCA model as first-level approximations to the health effects of toxic emissions. While several other indices covering a range of toxic effects have been proposed, data on these indices are available only for a few chemicals compared to CMU-ET (Horvath et al. 1995).

Fertilizer use (eutrophication): Eutrophication of the environment involves disturbance of ecological processes in water and soil due to an excessive supply of plant nutrients in the form of nitrogen compounds and phosphates. As a result of eutrophication, plant species that thrive in low-nutrient environments disappear. Also, increasing nitrate levels in ground water affect drinking water quality (Adriaanse 1993). The main agents responsible for eutrophication are phosphates and nitrates. The main sources are application of fertilizers and manure to soil in agriculture, and discharge of wastewater into surface water. The actual eutrophication effect from fertilizer use depends on application rates, frequency, runoff, soil conditions, topography, background concentrations, and distance and size of the water bodies. Fertilizer purchases/dollar output by different industry sectors are included in the environmental impact matrix only as an indicator of potential eutrophication. Aggregate data on value of purchases of fertilizers by industry sectors are extracted from the US-IO work files. The price data are from the U.S. Census of Manufactures (U.S. Commerce 1987).

Conventional pollutants:[3] As discussed earlier, the data on consumption of various fuels by industry sectors are extracted from US-IO work files. Average combustion emission factors for various fuels from U.S. EPA's compilation of emission factors (U.S. EPA 1995a) and IPCC guidelines (IPCC 1995) were used to estimate total emissions of conventional pollutants from fuel use by various sectors. The pollutants covered include carbon dioxide, carbon monoxide, sulfur oxides, nitrogen oxides, methane, and volatile organic compounds. Non-fuel use-related process emissions are not currently included in the model.

Hazardous wastes: The U.S. law governing hazardous waste management, Resource Conservation and Recovery Act (RCRA), requires all large-quantity generators in the U.S. to report the quantities of hazardous wastes generated, managed on site, received from outside sources, and shipped to off-site treatment, storage, and disposal facilities. Sectoral intensities for hazardous waste generation, on-site management, and off-site shipments using the RCRA database at U.S. EPA were developed by Horvath (Horvath 1997). These have been included in the EIO-LCA environmental matrix.

Greenhouse gas emissions and Global Warming Potential: The main greenhouse gases (GHG) are water vapor, carbon dioxide, methane, nitrous oxide, chloroflurocarbons (CFCs), and halons. The degree to which GHGs contribute to the global warming process depends on their concentration in the troposphere and on their ability to absorb the heat radiated by the earth. This absorption capacity is expressed as Global Warming Potential (GWP) relative to carbon dioxide. (IPCC 1995; Wuebbles 1995; Adriaanse 1993). GWP of different pollutants are used as weighting factors in aggregating GHG emissions. The emissions of carbon dioxide, nitrogen oxides, and methane from fuel combustion were estimated as detailed earlier. The TRI list of chemicals includes most of the CFCs and halons. The data on the air emissions of CFCs and halons are from the 1993 U.S. Toxic Releases Inventory (U.S. EPA 1995b). These have been incorporated in the environmental impact matrix in EIO-LCA.

Acid rain and total acidification potential: The three main contributors to acid rain are sulfur oxides (SO_x), nitrogen oxides (NO_x) and ammonia. We include sulfur dioxide (SO_2) and NO_x emissions from fuel combustion. The data on ammonia releases are from the U.S. Toxic Releases Inventory (U.S. EPA 1995b). These emissions are aggregated using their relative acidification potentials as weighting factors. 1/2 mole (32 grams) of sulfur dioxide has the same acidification potential as 1 mole (46 grams) of nitrogen dioxide and 1 mole (17 grams) of ammonia (Adriaanse 1993). Aeq is the aggregate acidification potential in SO_2 equivalents.

Stratospheric ozone depletion: Chlorofluorocarbons (CFCs) and bromofluorocarbons (halons), owing to their catalytic effect, trigger off a complex chain reaction that results in decomposition of ozone in the stratosphere. The extent to which these chemicals contribute to ozone depletion depends on the atmospheric concentrations, residence times of these chemicals in the atmosphere, and their ability to break down ozone. These effects are summarized in terms of ozone depletion potentials (ODP) of different chemicals relative to CFC_{11}. ODPs are an integral part of national and international considerations on ozone protection policy, including the Montreal Protocol and its amendments and the U.S. Clean Air Act (Wuebbles 1995). The sectoral emission factors of ozone-depleting chemicals were estimated from the U.S. TRI database by Horvath (1997) and were incorporated in the environmental impact matrix. The emissions were aggregated using their ODPs as weighting factors.

Application of Product Input-Output Life-Cycle Analysis: Steel versus Plastic Fuel Tank Systems for Automobiles

In this section, the use of the product EIO-LCA model is demonstrated with a case study comparing the life-cycle environmental performance of steel and plastic automobile fuel tank systems.

Beginning in the late seventies, there has been a significant movement towards more lightweight, composite materials in automobile components due to increasingly stringent fuel efficiency and weight reduction goals. As a part of this trend, attempts are underway to replace traditional steel fuel tanks in automobiles with tanks made from lighter plastic materials. It is forecast that by the year 2005 almost 60% of all passenger cars and light trucks produced in North America will have fuel tanks made from plastic materials (OSAT 1996). Modern multilayer plastic tanks meet the functional requirements and are cheaper. However, it is not clear if they are environmentally superior from a life-cycle perspective. Because millions of tanks are likely to be substituted, the overall environmental impacts can be significant.

General Motors Corporation (GM) is replacing traditional steel fuel tank systems on the select models of the GMT600 line of vans with new blow-molded, co-extruded, multi-layer, high-density polyethylene (HDPE) tank systems. These two tank systems were picked as examples. A conventional LCA study comparing equivalent designs of these two systems was conducted by GM and the National Pollution Prevention Center (NPPC), University of Michigan (Keoleian et al. 1997), and this paper draws on process descriptions and data in that study.

Each fuel tank system for the GM van consists of three major components: the tank that holds the fuel, straps that secure the tank to the automobile frame, and a shield. The steel tank requires a plastic shield to protect it from damage and corrosion from exposure to humidity, road salt, and stones, while the plastic tank requires a steel heat shield. For this comparative analysis, other components common to the two systems such as fuel lines, fuel filters, and sending units are excluded. The fuel tank in the steel tank system is made of plain carbon steel, with a nickel-zinc coating and a paint coat. The straps are made of hot-dipped galvanized steel with painted finish. The tank shield is made of HDPE. The fuel tank in the plastic tank system is a six-layer co-extruded plastic structure consisting of virgin and reground HDPE, adhesive layers, and an ethyl vinyl alcohol (EVOH) copolymer permeation barrier. The straps are made from hot-dipped galvanized steel coated with PVC. The heat shield is made from plain carbon steel. The designs of fuel tank systems can vary depending on the application. These two are picked for illustrating the method. The analysis can easily be modified to compare other designs.

The life cycle of a fuel tank consists of four main stages as shown in figure 1: fuel tank manufacture, use phase on the vehicle, shredding of auto hulk to recover ferrous scrap, and steel making from scrap steel in an electric arc furnace (EAF). For this analysis, we draw a boundary around each of these stages and treat them as hypothetical commodity sectors which draw inputs from the economy and produce some undesired emissions. The final recycling stage yields steel which is consumed by the economy. The value of inputs and environmental burdens at each stage is estimated. All the inputs at each stage are approximated by their corresponding US-IO commodity sectors. The economy-wide and hence life-cycle environmental implications are then estimated using EIO-LCA model II (equation 5). Because fuel tanks account for a very small fraction of the output of the sector "Motor Vehicle Bodies and Accessories," and fuel tanks are consumed almost exclusively by their own commodity sector, detailed disaggregation models would also result in very similar estimates. The aggregation of results from these stages provides a comprehensive life-cycle inventory.

Life-Cycle Assessment of Steel Fuel Tank

Life-cycle environmental burdens from inputs to steel tank manufacturing: The steel tank manufacturing process involves stamping, trimming, and piercing of sheet steel, welding, washing, testing, and assembly operations using inputs such as steel sheet, electricity, dies, and lubricants. The estimated value of inputs and the U.S. commodity sectors by which these inputs are approximated are shown in the first 13 rows of table 2. These estimates are partly based on the GM-NPPC study and partly on the input purchases by the automotive stamping sector as reported in the U.S. input-output tables (Keoleian et al. 1997; U.S. Commerce 1994). The economy-wide environmental burdens to meet a final demand vector equivalent of these inputs are estimated using equation (3) and shown in table 3.

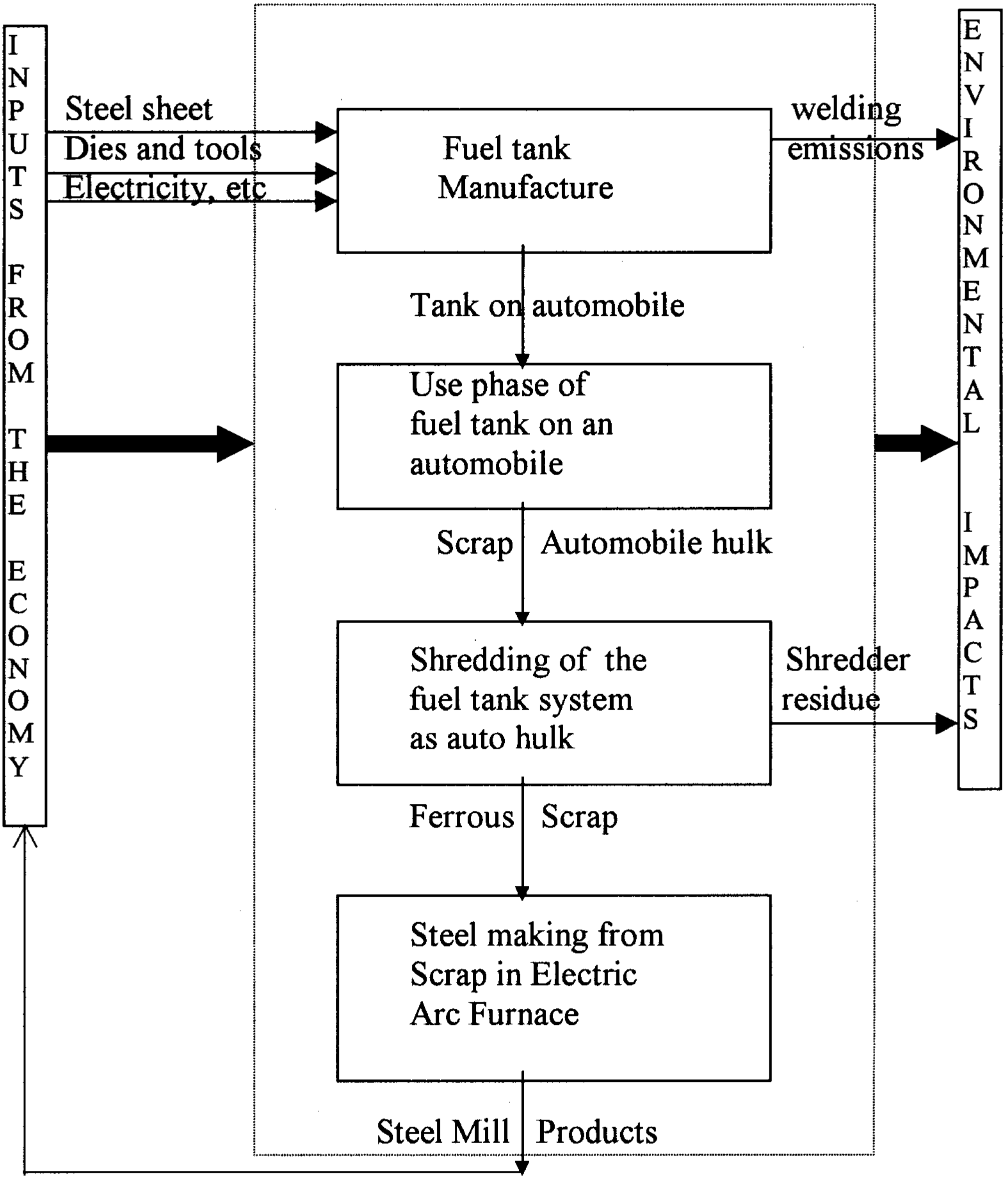

Figure 1 Life-cycle stages of an automobile fuel tank system.

Direct environmental burdens at the manufacturing stage: Electricity and natural gas are the main sources of energy in manufacturing. The energy associated with fuel use in electricity generation has already been accounted for in the input materials. Hence, the energy consumption in the manufacturing stage is 73.53MJ/tank from natural gas use. Airborne emissions in steel tank manufacture are mainly from welding operations. Based on the data from the GM plant, Keoleian and colleagues (1997) report air emissions of 0.2651 g of metals like zinc, chromium, manganese, and nickel, 1.841 g of particulates, and 0.684 g of volatile organic compounds per tank from steel tank manufacturing. Additional emissions from burning of 1.29 kg (2.84 lb) of natural gas for process heat and other requirements are included. Waterborne emissions in steel tank manufacturing are mainly from tank washing to remove the lubricant. The upper

Table 2 Steel fuel tank: Input requirements at different life-cycle stages

Input code	*US-IO commodity sector used as approximation*	*US-IO sector code*	*Dollar value of input/tank*
Inputs to Tank Manufacturing			
Carbon steel sheet	Blast Furnaces and Steel Mill Products	370101	23.530
HDPE shield material	Plastics and Resins (HDPE Shield)	280100	1.940
Stamping, trimming dies	Dies, Tools and Machine Accessories	470300	2.850
Transportation of finished tanks	Motor Freight Transportation	650300	0.930
Electricity	Electric Utilities	680100	0.850
Transportation of raw materials	Railroad Transportation	650100	0.270
Galvanizing and coating	Plating and Polishing Services	420401	0.270
Natural gas for boilers	Gas Production and Distribution	680200	0.200
Packing materials	Paper and Paperboard Containers	250000	0.170
Paints	Paints and Allied Products	300000	0.110
Bearings and other repairs	Ball and Roller Bearings	490200	0.100
Detergents for washing tanks	Soaps and Detergents	290201	0.020
Lubricants and coolants	Lubricants and Greases	310102	0.020
Inputs to Use Phase			
Gasoline	Petroleum Refining	310101	13.720
Inputs to Auto Shredding			
Electricity	Electric Utility Services	680100	0.055
Transportation of hulks & scrap	Motor Transportation	650300	0.500
Shredder tools and repairs	Dies, Tools, and Machine Accessories	470300	0.102
Inputs to EAF Steel Making*			
Limestone, lime, florspar	Lime and Limestone	361300	0.076
Refractories	Non-clay Refractories	362100	0.060
Electrodes	Carbon & Graphite Products	530700	0.208
Ferroalloys	Electro-metallurgical Products	370102	0.069
Electricity	Electric Utilities	680100	0.495
Natural gas	Gas Distribution	680200	0.062
Maintenance of EAF supplies	Industrial Electric Equipment	530800	0.131
Insurance	Insurance	700500	0.033
Semi-finished Steel Recovered in EAF			
Blast furnaces and steel mill products		370101	– 4.397

* These numbers are based on CMP (1987).

limit estimates of water emissions/steel tank based on the treatment plant data are reported in the GM-NPPC study as 16.873 g of metals and 170.8 g of oil and grease. These metal emissions are included in the inventory of toxic chemical releases.

Environmental impacts during the use phase of a steel tank: The use-phase environmental impacts are the sum of the life-cycle burdens of inputs to the use phase and the impacts during use itself. There is no independent use phase for a fuel tank, except as a component of an assembled vehicle. Relevant portion of the environmental burden associated with use phase of the complete vehicle has to be allocated to the fuel tank. The typical environmental burdens during the vehicle use phase cover life-cycle burdens of various material inputs such as fuel, lubricants, coolants, tires, and repairs and maintenance services over the lifetime of the vehicle, and the

Table 3 Select economy-wide impacts from production of inputs for one million steel tanks

Impact area	*Units*	*Quantities*
Economic Impact		
Value of direct inputs	$ Million	31.26
Economy-wide increase in output	$ Million	68.94
Non-renewable Ores Consumed		
Iron ore	MT*	40,942
Copper ore	MT	4,464
Gold and silver ores	MT	9,607
Energy Consumption		
Bituminous coal	MT	33,958
Natural gas	MT	2,598
Motor gasoline	MT	339
Light fuel oils	MT	1,250
Heavy fuel oils	MT	781
Electricity	Mill. kWh	42.8
TOTAL ENERGY	Million MJ	1,499
Fertilizers Used	MT	99
Toxic Releases		
TRI air releases	Kilograms	17,024
TRI water releases	Kilograms	3,092
TRI total environmental releases	Kilograms	51,994
CMU-ET toxicity-weighted total env. releases	kg H_2SO_4 eq.	131,956
Conventional pollutants		
SO_x	MT	1,192.3
NO_x	MT	402.2
Methane	MT	1.53
Volatile organic chemicals	MT	13.89
Carbon dioxide	MT	99,508
Carbon monoxide	MT	77.8
RCRA hazardous wastes generated	MT	2,894
Summary Indices		
Global Warming Potential (GWP)	MT CO_2 eq.	216,313
Ozone Depletion Potential (ODP)	kg CFC11 eq.	27.9
Acidification Potential (Aeq)	kg SO_2 eq.	404,066

* MT: metric tons

tail pipe emissions. We assume that the fuel tank contributes to vehicle use-phase environmental impacts only in terms of additional fuel consumption due to its weight, and ignore incremental contributions to other inputs and services. Keoleian and colleaugues (1997) estimate the contribution of the steel tank system to vehicle lifetime fuel consumption to be 23.3 gallons (8.82 liters) (Keoleian et al. 1997). The value of this gasoline consumption is $13.72 in 1987 dollars. Because gasoline is a typical output of the "Petroleum Refining" sector (US-IO Sector Number 310101), the life-cycle environmental burdens associated with production of gasoline are approximated by the economy-wide environmental impacts associated with an increase of $13.72 in the final demand for the output of the petroleum refining sector. Even though gasoline is only one of the many joint products from petroleum refining, this procedure allocates the environmental burdens of refining to different refinery products on the basis of their relative market value.

The life-cycle energy associated with the use phase is 3.37 GJ/steel tank, (3.19×10^6 BTU/tank) consisting of heating value of 23.3 gallons (88.2 liters) of gasoline, and the life-cycle energy of 316 MJ associated with production of gasoline.

The use-phase emissions are the vehicle emissions allocated to the fuel tank based on its contribution to lifetime fuel consumption. Keoleian and colleagues (1997) estimate that the 1996 G-van emits 1,969 kg of carbon monoxide, 101.2 kg of hydrocarbons and 220 kg of nitrogen oxides over a lifetime travel of 110,000 miles (177,028 kilometers). These emissions are allocated to the steel tank in proportion to its contribution to the lifetime vehicle fuel consumption of 6,707 gallons.

Environmental burdens of steel tank scrap processing: The prompt scrap produced during steel tank manufacturing and the steel recovered from the auto hulk at the end of vehicle life are used as scrap input into steel production. A total of 21.26 kg of steel scrap per tank enters the shredding process and we assume that 100% of its weight is recovered as processed scrap. Sterdis (1997) estimates that a ton of auto hulk processing consumes about 53.6 kWh (0.193 GJ) of electricity, and $5.90 worth of tools and maintenance service. Motor transportation costs per steel tank are estimated to be $0.614 (Keoleian et al. 1997). These inputs to recycling are approximated of their industry sectors. The estimated (1987) dollar values and corresponding US-IO sectors are shown in table 2. The life-cycle environmental burdens of these inputs are estimated using equation (3). Direct environmental burdens from the shredding operation include energy consumption in shredding (1.13 kWh per tank) and automobile shredder residue (ASR), which is landfilled. It is assumed that the HDPE shield will be a part of ASR and landfilled as hazardous waste.

Environmental burdens of steel recovery from scrap in an electric arc furnace: All the ferrous scrap recovered from the fuel tank systems is assumed to be re-melted in electric arc furnaces (EAF) to produce steel mill products. Each steel fuel tank yields 21.26 kg of processed scrap, which can be processed into 20.24 kg of semi-finished steel mill products valued at $4.397. The various inputs required for EAF recycling and the US-IO sectors by which they are approximated are shown in table 2. Estimates of input requirements are based on a report on electric steel making by the Center for Metals Production (CMP 1987). The separately estimated direct emissions and energy use from EAF steel making are included in table 4. This output of steel mill products is assumed to reduce the final demand for the output of the industry sector "Blast Furnaces and Steel Mills (US-IO Number 370101)" by a corresponding amount. The environmental credits for recycled steel are the avoided economy-wide, environmental burdens from $4.397 worth of steel mill products substituted by the recycled steel.

Select environmental burdens over different life-cycle stages of the steel tank are summarized in table 4.

Life-Cycle Assessment of Plastic Fuel Tank

The environmental burdens of the plastic fuel tank system over its entire life cycle, covering production of input materials, manufacturing, use phase, and end-of-life management, are analyzed using similar steps, as in the case of the steel tank. Estimates of inputs and direct environmental burdens at each life-cycle stage were developed. The economy-wide environmental burdens from these inputs were calculated using EIO-LCA model II (equation 5). The input requirements at various life-cycle stages of the plastic tank and corresponding commodity sectors are shown in table 5 .

The plastic tank manufacturing process begins with the mixing of resin with appropriate additives in separate mixing vessels. These mixtures correspond to the composition of the six layers of the tank, namely virgin HDPE with carbon black, reground HDPE, an adhesive layer, ethyl vinyl alcohol (EVOH) co-polymer permeation barrier, another adhesive layer, and virgin HDPE. These mixtures are fed through six individual extruders to produce layers just before entering the blow molder. The polymer layers are simultaneously blow molded to the required shape of the tank. The multi-layer tank is then sent to the piercing and machining station. Components such as rollover valves and clips are welded onto the tank, followed by assembly of the sending unit, straps, shield, and fuel lines. All finished tanks are then packed, placed on shipping racks, and sent to the vehicle assembly plant by truck. The initial part of table 5 shows the estimated dollar value of inputs from different commodity sectors for plastic tank manufacture. Their life-cycle burdens are summarized in table 6.

Direct environmental burdens during manufacturing of plastic tanks: The major source of emissions in plastic tank manufacturing is the extrusion–blow molding process. Emission factors for HDPE blow molding process from Barlow (Barlow et al. 1996) were used to estimate process emissions during plastic tank manufacturing. In addition, emissions from burning natural gas for process heat and other requirements, estimated at 1.0 gram of carbon monoxide, 3.25 kg of CO_2, 3.91 grams of NO_x and 0.08 grams of methane per tank, are included.

Environmental burdens in the use phase of the plastic tank: As in the case of steel tanks, the life-cycle impacts of gasoline production and exhaust emissions during vehicle use are allocated to the fuel tank. The gasoline use allocated to the plastic fuel tank is 14.95 gallons valued at $8.80. The GM-NPPC study estimates that the G-Van, fitted with a plastic tank, consumes 6,699 gallons of gasoline over its lifetime (110,000 miles), and emits 1,967 kg of carbon monoxide, 101 kg of hydrocarbons, 219.7 kg of NO_x, and 58,733 kg of carbon dioxide. These use-phase emissions are allocated to the plastic fuel tank based on its weight.

Environmental burdens from recovery of steel from the plastic fuel tank: For this analysis, it is assumed that the whole tank system is shredded, i.e., there is no disassembly of components prior to shredding. That is, the tank system weighing 14.6 kg enters the shredding operation, from which 3.41 kg of steel corresponding to the shield, straps, and prompt scrap will be recovered and the balance, 11.2 kg, will be landfilled as automobile shredder residue. The input requirements for the shredding operation and the economy-wide environmental burdens are estimated along the same lines as the steel tank.

As in the case of the steel tank, all the ferrous scrap from the plastic fuel tank system is assumed to be processed into semi-finished steel mill products by re-melting scrap in an electric arc furnace: 3.41 kg/tank of steel scrap entering the EAF process yields 3.25 kg of semi-finished steel mill products valued at $0.70. The credit for recycled steel is estimated similarly.

A summary of the environmental burdens over the entire life cycle of the plastic fuel tank is shown in table 6.

Comparison of Steel and Plastic Fuel Tank Life-cycle Environmental Impacts

A summary comparison of the total life-cycle environmental impacts of the two fuel tank systems is presented in table 7. Comparative decomposition by life-cycle stages of selected impacts is presented in the form of a series of graphs in figures 2–7.

From table 7, it is apparent that the total life-cycle environmental burdens from the steel fuel tank are larger than the burdens from the plastic fuel tank, on all the dimensions except RCRA hazardous generation and total ozone depletion potential (ODP) of air emissions. The environmental impacts from the steel tank as a percentage of impacts from the plastic tank range from 125% for total TRI toxic chemical releases to the environment, to 3,842% for net iron ore use. From tables 4 and 6, and figures 2–7, it can be seen that the environmental burdens from the steel fuel tank are larger than the burdens from the plastic fuel tank in most of the individual life-cycle stages also.

In conclusion, the EIO-LCA suggests that if all other performance parameters were equal, the plastic tank would be preferable in this application, on the basis of its relatively better environmental performance.

Comparison with Results from the GM-NPCC Study

As mentioned, General Motors and National Pollution Prevention Center, University of Michigan (GM-NPCC) carried out a conventional life-cycle inventory of these two fuel tank systems. The boundaries of analysis, data sources,

Table 4 Summary of life-cycle environmental burdens of the steel tank system (per tank)

Environmental impact	*Inputs to manufacturing*	*Manu-facturing*	*Inputs to use phase*	*Use phase*	*Inputs to shredding*	*Shredding*	*EAF steel making*	*Credit for EAF steel*	TOTAL
Energy									
Coal (kg)	34.00	0.00	1.42	0.00	0.190	0.00	1.58	–5.73	31.46
Nat. gas and LNG (kg)	2.80	1.29	3.26	0.00	0.018	0.00	0.18	–0.38	7.168
Petroleum fuels (kg)	2.70	0.00	1.80	65.00	0.193	0.00	0.15	–0.34	69.503
Electricity (kWh)	42.80	17.7	4.80	0.00	0.10	1.13	1.12	–7.07	60.58
Total energy (MJ)	1499	73.50	316	3055	10.20	4.10	61	–191	4827.8
Toxic Releases (g)									
Air	17.02	0.27	4.39	0.00	0.06	0.00	0.76	–2.33	20.17
Water	3.09	0.02	0.33	0.00	0.01	0.00	0.21	–0.48	3.18
Land & underground	31.88	0.00	1.83	0.00	0.03	0.00	0.71	–5.14	29.31
Total env. releases	51.99	0.29	6.56	0.00	0.11	0.00	1.68	–7.96	52.67
Releases + transfers	258.3	0.29	58.10	0.00	0.39	0.00	32.79	–43.74	306.13
Toxicity-Weighted Releases H_2SO_4eq g									
Air	10.72	0.17	0.42	0.00	0.02	0.00	0.55	–1.87	10.01
Water	2.14	0.02	0.16	0.00	0.01	0.00	0.05	–0.34	2.04
Land & underground	119.10	0.00	2.44	0.00	0.12	0.00	4.06	–20.60	105.12
Total env. releases	131.95	0.19	3.02	0.00	0.15	0.00	4.66	–22.81	1117.16
Releases + transfers	834.60	0.19	61.22	0.00	1.01	0.00	115.70	–148.6	864.08
Conventional Air Pollutants (g)									
SO_x	1192	0.00	51.95	0.00	7.07	0.00	56.87	–200.20	1107.69
NO_x	402	3.91	31.20	760	3.86	0.00	19.0	–66.42	1153.55
Methane	1.54	0.08	0.41	41.6	0.04	0.00	0.08	–0.23	43.52
VOCs	13.89	0.68	3.55	350	0.63	0.00	0.47	–1.90	367.32
CO	77.84	1.0	17.27	6840	5.05	0.00	2.60	–10.42	6933.34
CO_2 (kg)	99.51	3.25	17.11	206.2	1.11	0.00	4.85	–16.20	315.83
RCRA Waste (kg)									
Generated	2.89	0.00	9.40	0.00	0.03	3.34	0.34	–0.36	15.64
Managed	1.94	0.00	8.90	0.00	0.03	0.00	0.03	–0.23	10.67
Nonrenewable Ores									
Iron ore (kg)	40.94	0.00	0.12	0.00	0.015	0.00	0.01	–7.58	33.505
Copper ore (kg)	4.52	0.00	0.23	0.00	0.024	0.00	0.57	–0.68	4.664
Gold, silver ores (kg)	9.61	0.00	0.10	0.00	0.014	0.00	0.09	–1.71	8.104
Summary Indices									
GWP (kg CO_2 eq)	216.30	4.38	26.17	427.1	2.23	0.00	10.37	–35.47	651.08
ODP (g CFC_{11} eq)	0.03	0.00	0.002	0.00	0.00	0.00	0.001	–0.002	0.031
Aeq (g SO_2 eq)	404.0	2.72	27.88	529.0	3.40	0.00	19.29	–67.08	919.21

Table 5 Plastic fuel tank: Input requirements at different life-cycle stages

Input	*Commodity sector used as an approximation*	*EIO sector code*	*Dollar value of input/tank*
Inputs to Plastic Tank Manufacture			
HDPE, PVC, EVOH	Plastics and Resins	280100	7.60
Steel straps and shield	Automotive Stampings	410201	3.52
Electricity	Electric Utility Services	680100	1.38
Glycol and other supplies	Industrial Org. & Inorg. Chemicals	270100	0.85
Natural gas	Gas Production	680200	0.20
Packing materials	Paperboard and Containers	250000	0.69
Molder spare parts	Special Industry Machinery Parts	480600	0.24
Carbon black	Carbon Black	270405	0.10
Adhesive layer material	Adhesives and Sealants	270403	0.15
Inputs to Use Phase			
Gasoline	Petroleum Refining	310101	8.80
Inputs to Auto Shredding			
Electricity	Electric Utility Services	680100	0.038
Transportation of hulks & scrap	Motor Transportation	650300	0.343
Shredder tools and repairs	Dies, Tools and Machine Accessories	470300	0.070
Inputs to EAF Steel Making			
Limestone, lime, florspar	Lime and Limestone	361300	0.01175
Refractories	Non-clay Refractories	362100	0.00969
Electrodes	Carbon & Graphite Products	530700	0.00334
Ferroalloys	Electro-metallurgical Products	370102	0.00112
Electricity	Electric Utilities	680100	0.07940
Natural gas	Gas Distribution	680200	0.00995
Maintenance of EAF supplies	Industrial Electric Equipment	530800	0.02101
Insurance	Insurance	700500	0.00533
Semi-finished Steel Recovered in EAF			
Blast furnaces and steel mill products		370101	– 0.700

coverage, and classification of environmental burdens in the GM-NPPC study are different from EIO-LCA. In the analysis of materials production phase, the GM-NPCC study considers only steel, HDPE, PVC, and EVOH. The environmental data on steel are from a European database on packing materials (FOEFL 1991). The data on PVC and HDPE are from other European databases (Boustead 1993, 1994). EVOH is approximated by HDPE. In EIO-LCA, steel is approximated by the U.S. steel sector, and all plastics are approximated by the U.S. plastics materials and resins sector. Similarly, GM-NPCC use proprietary information from Franklin Associates for the life-cycle burdens from gasoline production. The GM-NPCC study reports the following environmental burdens: energy consumption, solid waste generation, air emissions of CO_2, CO, NO_x, hydrocarbons and particulate matter, and water effluents covering suspended solids, dissolved solids, oil and grease, and metals. These are different from those covered in EIO-LCA. As a result, only a limited direct comparison is possible between the results from these two studies. The common elements are summarized in table 8.

Two things are noticeable about the comparative results. One, despite using very different

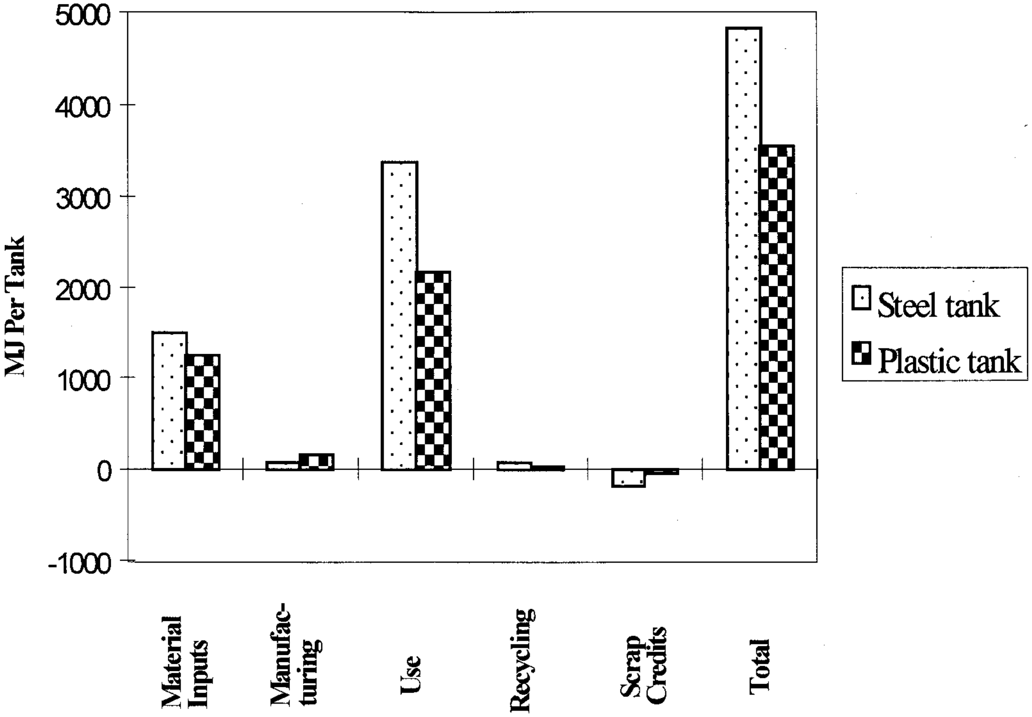

Figure 2 Total energy.

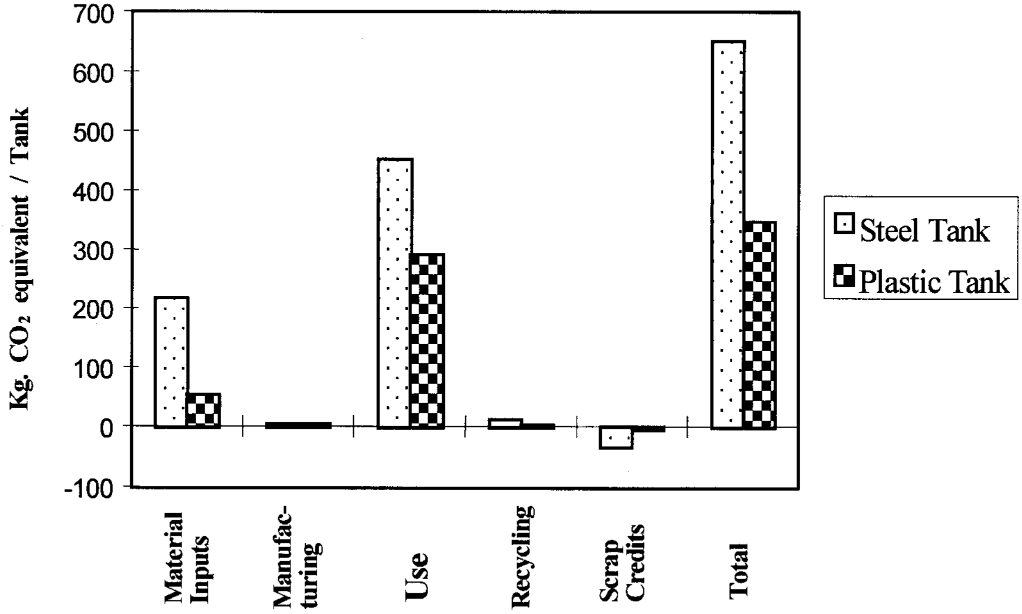

Figure 3 Global Warming Potential.

Table 6 Summary of life-cycle environmental burdens of the plastic tank system (per tank)

Environmental impact	*Inputs to manufacturing*	*Manu-facturing*	*Inputs to use phase*	*Use phase*	*Inputs to shredding*	*Shredding*	*EAF steel making*	*Credit for EAF steel*	*TOTAL*
Energy									
Coal (kg)	7.43	0	0.91	0.00	0.13	0.00	0.26	–0.92	7.81
Nat. gas and LNG (kg)	1.69	1.29	2.10	0.00	0.01	0.00	0.03	–0.06	5.06
Petroleum fuels (kg)	1.10	0	1.16	41.71	0.13	0.00	0.03	–0.05	44.08
Electricity (kWh)	16.1	23	3.08	0.00	0.07	0.78	0.18	–1.14	42.07
Total energy (MJ) *	1246	156.8	202.8	1960	7.00	2.82	10.0	–31	3555
Toxic Releases (g)									
Air	17.22	0.45	2.82	0.00	0.04	0.00	0.12	–0.37	20.28
Water	2.23	0	0.21	0.00	0.01	0.00	0.03	–0.08	2.4
Land & underground	18.99	0	1.17	0.00	0.02	0.00	0.12	–0.83	19.47
Total env. releases	38.38	0.45	4.21	0.00	0.08	0.00	0.27	–1.28	42.11
Releases + transfers	89.38	0.45	37.28	0.00	0.27	0.00	5.26	–7.02	125.62
Toxicity Weighted Releases H_2SO_4eq g									
Air	2.26	0.16	0.27	0.00	0.02	0.00	0.08	–0.30	2.49
Water	1.44	0	0.10	0.00	0.01	0.00	0.01	–0.06	1.5
Land & underground	34.44	0	1.57	0.00	0.08	0.00	0.65	–3.30	33.44
Total env. releases	38.14	0.16	1.94	0.00	0.10	0.00	0.75	–3.66	37.43
Releases + transfers	110.84	0.16	39.28	0.00	0.69	0.00	18.56	–23.84	145.69
Conventional Air Pollutants (g)									
SO_x	266.89	0.00	33.33	0.00	4.86	0.00	9.12	–32.11	282.09
NO_x	92.24	3.91	20.02	488	2.65	0.00	3.05	–10.65	599.22
Methane	0.54	0.08	0.26	27.2	0.03	0.00	0.01	–0.04	28.08
VOCs	5.56	0.45	2.28	225	0.43	0.00	0.07	–0.30	233.49
CO	26.21	1.00	11.07	4390	3.47	0.00	0.42	–1.67	4430.5
CO_2 (kg)	26.03	3.25	10.97	132.3	0.76	0.00	0.78	–2.60	171.49
RCRA Waste (kg)									
Generated	2.34	0	6.03	0.00	0.02	11.20	0.05	–0.06	19.58
Managed	2.06	0	5.71	0.00	0.02	0.00	0.01	–0.04	7.76
Nonrenewable Ores									
Iron ore (kg)	2.00	0	0.08	0.00	0.01	0.00	0.002	–1.22	0.872
Copper ore (kg)	1.18	0	0.15	0.00	0.02	0.00	0.09	–0.11	1.33
Gold & Silver ore (kg)	0.78	0	0.06	0.00	0.01	0.00	0.02	–0.27	0.60
Summary Indices									
GWP (kg CO_2 eq)	54.22	4.38	16.78	274.1	1.53	0.00	1.66	–5.69	346.98
ODP (g CFC_{11} eq)	0.05	0.00	0.001	0	0.00	0.00	0.00	0.00	0.051
Aeq (g SO_2 eq)	95.7	2.72	17.88	339.6	2.34	0.00	3.09	–10.76	450.57

*Energy including the heating values of HDPE, PVC & EVOH (78.3, 31.5 & 52 MJ/kg respectively).

Table 7 Comparison of total life-cycle environmental impacts of steel and plastic fuel tanks

Environmental impact	*Plastic tank impacts*	*Steel tank impacts*	*Steel tank impacts as % of plastic tank impacts*
Energy Use			
Coal (kg)	7.81	31.46	403
Nat. gas and LNG (kg)	5.06	7.168	142
Petroleum fuels (kg)	44.08	69.503	158
Electricity (kWh)	42.07	60.58	144
Total energy (MJ) *	3555	4827.8	136
Toxic Releases (g)			
Air	20.28	20.17	99
Water	2.4	3.18	133
Land & underground	19.47	29.31	151
Total env. releases	42.11	52.67	125
Releases + transfers	125.62	306.13	244
Toxicity-Weighted Releases H_2SO_4eq g			
Air	2.49	10.01	402
Water	1.5	2.04	136
Land & underground	33.44	105.12	314
Total env. releases	37.43	117.16	313
Releases + transfers	145.69	864.08	593
Conventional Air Pollutants (g)			
SO_x	282.09	1107.69	393
NO_x	599.22	1153.55	193
Methane	28.08	43.52	155
VOCs	233.49	367.32	157
CO	4430.5	6933.34	156
CO_2 (kg)	171.49	315.83	184
RCRA Waste (kg)			
Generated	19.58	15.64	80
Managed	7.76	10.67	138
Nonrenewable Ores			
Iron ore (kg)	0.872	33.505	3842
Copper ore (kg)	1.33	4.664	351
Gold, silver ores (kg)	0.6	8.104	1351
Summary Indices			
GWP (kg CO_2 eq)	346.98	651.08	188
ODP (g CFC_{11} eq)	0.051	0.031	61
Aeq (g SO_2 eq)	450.57	919.21	204

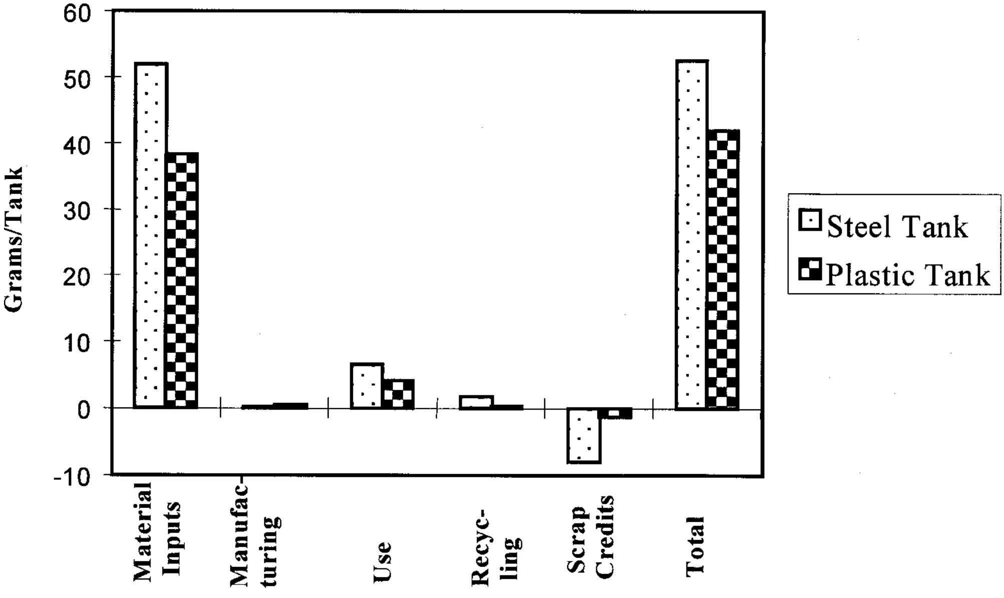

Figure 4 Total toxic releases to the environment.

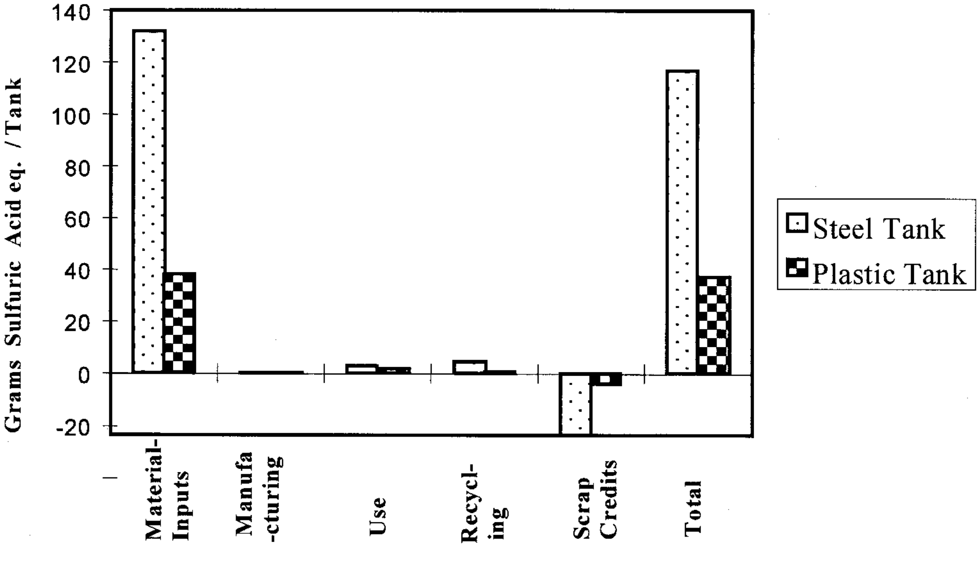

Figure 5 Toxicity-weighted environmental releases.

data sources, methodologies, and levels of aggregation, there is a high degree of correspondence between the comparable results from these two studies. The qualitative conclusions from the two studies are the same: that the plastic tank appears to perform better on most of the environmental dimensions except solid waste generation; and use-phase impacts dominate total life-cycle energy use and life-cycle conventional pollutant emissions. Second, contrary to the expectation that EIO-LCA would report higher impacts due to greater coverage, the absolute amount of impacts reported in EIO-LCA here are generally lower than those reported in the GM-NPPC study (except solid waste generation). The energy consumption in the materials production stage is higher in the case of EIO-LCA as expected. Though both studies use the

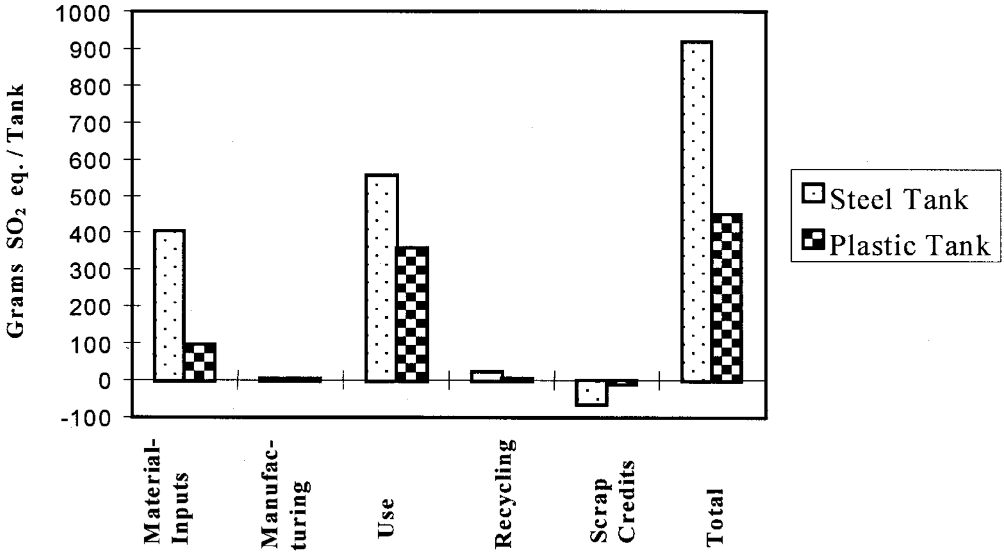

Figure 6 Acidification potential of air emissions.

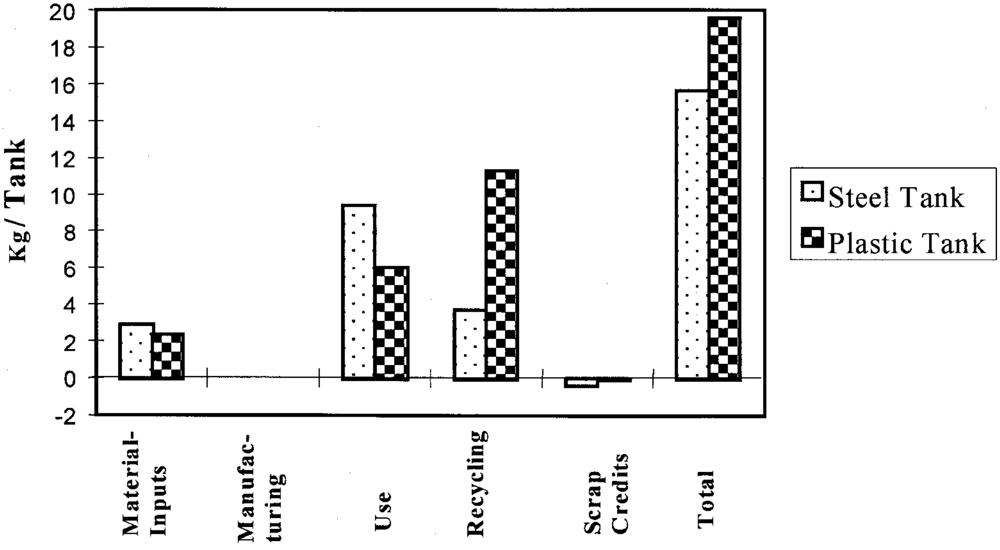

Figure 7 RCRA hazardous waste generation.

same quantities of gasoline to estimate use phase energy, unit energies are different. While the GM-NPPC uses total energy (precombustion + combustion) of 42.03 MJ/liter of gasoline, the estimated precombustion + combustion energy content of gasoline in EIO-LCA is 38.2 MJ/liter. Because the GM-NPPC estimate is from a proprietary source, we can not pinpoint the source of the difference. However, it is most likely due to differences in allocations between co-products in petroleum refining. EIO-LCA also provides energy credits for recycled steel. The GM-NPPC study uses heating value of 81 MJ/kg of HDPE while EIO-LCA uses 78.3 MJ/kg of HDPE. If these estimates were used in EIO-LCA, the total life-cycle energy in EIO-LCA would be higher than those reported in the GM-NPPC study.

Table 8 Comparison of results from EIO-LCA and GM-NPCC LCA

Burden *Category*	*GM-NPPC*	*Steel tank* *EIO-LCA*	*GM-NPPC*	*Plastic Tank* *EIO-LCA*
Life-cycle energy MJ/tank	4860	4828	3631	3555
Energy in material production MJ/tank	1020	1499	1020	1246
Energy in use phase MJ/tank	3710	3371	2360	2163
Energy in EOM MJ/tank	14	–126	13	–21
Life-cycle CO_2 emissions kg/tank	295	316	191	172
Life-cycle CO emissions g/tank	7014	6933	4524	4431
Life-cycle NO_x emissions g/tank	1284	1154	942	600
Life-cycle VOC emissions g/tank	1381	367	894	234
Life-cycle solid waste kg/tank	13.4	15.64(haz)	14.5	19.6(haz)

A major limitation of the current EIO-LCA is that it reports conventional pollutant emissions from fuel combustion only and does not include non-fuel process emissions. Process emissions are included in the GM-NPPC study. HDPE and PVC manufacturing involve significant process emissions of NO_x and VOCs. According to Boustead (1993), these total to 21 g of VOCs and 10 g of NO_x per kg of HDPE, and 19 g of NO_x and 26 g of VOCs per kg of PVC. Inclusion of these process emissions in EIO-LCA is necessary for comparability of conventional pollutant emissions. If we add only these direct NO_x and VOC emissions to the reported EIO-LCA emissions, the resultant emission numbers will be larger than the emissions reported in the GM-NPPC study.

Discussion and Conclusions

This paper extends and refines the EIO-LCA model to make it a practical and flexible tool for comprehensive product life-cycle assessment that can be used by companies, regulators, and consumer groups to conduct quick, cost-effective, and comprehensive life-cycle assessments. The extension enables life-cycle assessment of individual products, comparison of products that may belong to the same sector or completely new products, and incorporation of environmental impacts from product use phase and end-of-life management (reuse, remanufacturing, recycling) stages in EIO-LCA. The extension combines together comprehensive environmental impact coefficient matrices for the U.S. economy, covering fuel and energy use, conventional pollutant emissions, fertilizer use, and non-renewable ore use from publicly available sources. The proposed methodology is demonstrated by applying it to a real-life decision problem of evaluating environmental performance of alternative fuel tank systems.

The proposed EIO-LCA method, however, has several potential limitations that have to be considered while applying the method. These limitations and caveats arise both from the nature of input-output analysis and from the specific character of this method. EIO-LCA shares the fundamental limitations of input-output analysis, such as: linear approximation in technical coefficients, static analysis, and omission of capital services. Static analysis and linearity provide good approximations for relatively small changes, typical in product LCA. Because capital services are consumed over a large number of individual units, the environmental impacts from capital services are likely to be small.

Expressing all the environmental impact coefficients in terms of environmental burden/dollar value of sector output instead of familiar physical units such as tons, liters, service hours, and so on makes modeling simpler by avoiding the difficulty of incorporating multiple physical units and appropriate conversion factors in the model. Under constant price conditions, these impact coefficients can easily be translated to physical unit bases. However, geographical, temporal and tax-related variations in prices can introduce errors. Care should be taken to use appropriate price indices to adjust for these variations to reflect national average producer prices in the base year.

Co-product allocation is a much-debated topic in both construction of national input-output tables and LCA literature (Miller and Blair 1985, Curran 1996). In the construction of US-IO tables, a commodity technology assumption is used in estimating technical coefficients for co-products (refer to U.S. Commerce 1994 for more details). EIO-LCA allocates environmental burdens on the basis of market value. Other bases of allocation used in the LCA literature include mass, dry mass, energy content, incremental processing energy, stoichiometry, and heat of reaction (Curran 1996, SETAC 1993, Boustead 1993). For some specific systems, one of these allocation methods might be more appealing than other methods. Science does not dictate the method of allocation. Market value can be a reasonable basis when higher prices reflect increased processing and emissions.

In deriving the U.S. input-output tables, the technical coefficients for comparable imports are assumed to be similar to the corresponding domestic U.S. industry sectors (U.S. Commerce 1994). The EIO-LCA models assume that the environmental burden coefficients of imports are also well-approximated by the corresponding U.S. domestic industry sectors. This may introduce errors in analyses of products with high import content and very different foreign production technologies. Conceptually, creation of appropriate hypothetical industry sectors (Model II) representing the technology of such imports can address the issue.

Because data from many different sources and time periods have been collected, normalized, aggregated, and averaged to arrive at sector-level environmental indices, there are significant uncertainties in the estimates.[4] First, there are uncertainties in the national technical coefficient matrix arising from aggregation, sampling errors, imputation procedures for missing data, co-product allocation procedures, and linearity assumptions. The data on dollar value of purchases of fuels, fertilizers, and ores are from the US-IO work files. The quantities were derived using an average producer price, which overlooks regional and quality-related price variations and inventory changes. Large uncertainties are associated with the U.S. TRI data. Many industries such as mining and utilities until recently were excluded from reporting. Similarly, only facilities employing at least ten people or using at least 1,000 lb/year of the toxic chemicals are required to report. A study by the U.S. General Accounting Office concluded that reported TRI releases might be as low as 5% of the actual toxic releases (U.S. GAO 1991). As a result, the TRI release data in the model are likely to be an underestimate. The conventional pollutant emissions are based on generic emission factors for the primary use of different fuels. Variations in emissions due to non-linearity over the operating range and differences in fuel quality, combustion technology, and efficiencies have been overlooked in using these generic emission factors. Non-fuel combustion-related emissions are not currently included in the model due to the unavailability of data. Attempts are underway to include data on non-fuel process emissions estimated from the AIRS (Aerometric Information Retrieval System) database of U.S. EPA into EIO-LCA. However, the major strength of EIO-LCA is that the national averages (and derived estimates for disaggregated sectors) are mainly used as approximations for missing data and all the available more accurate data can be included in the model. More detailed models will be less affected by errors in aggregate data. Results from the cruder models should be interpreted more as indicators of relative performance in comparing products than as absolute performance indicators.

In conclusion, EIO-LCA is a flexible and powerful addition to the toolkit of LCA practitioners. In its simpler forms it serves as an initial screening device for scoping and prioritizing data collection. More advanced models can be used to validate results at different stages of a conventional LCA to check if boundary definitions and consideration of economy-wide interdependencies affect results. Efforts are underway to offer EIO-LCA as a web-based software in the public domain.

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Notes

1. There is a vast theoretical and empirical literature on extension of input-output techniques for environmental analysis (for example, see Ayres and Kneese 1969; Cumberland and Stram 1976; Forsund 1985; Duchin et al.1990; Duchin 1994; Lutz 1993; UN 1993). However, most of them are aimed at broad national-level policy analysis. In that respect, the current application for micro-level product and process evaluation is novel.
2. I do not attempt to quantify or monetize the final health and ecological impacts. These involve many other difficult conceptual and empirical issues.
3. In U.S. regulatory jargon, conventional pollutants refer to carbon monoxide, sulfur oxides, nitrogen oxides, methane, and volatile organic compounds. In the analysis described in this article, carbon dioxide is included in this category as well.
4. Data quality is a major concern of LCA practitioners and many formal quantitative and qualitative indicators of data quality in LCA have been proposed (see Vigon et al. 1993 and references therein). However, only qualitative descriptions of data quality are provided here due to time and data constraints.

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