GREEN DESIGN

Economic Input-Output Models for Environmental Life-Cycle Assessment

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Process and product models are commonly used for performing life-cycle assessments (LCAs) of the environmental impacts of materials and products through different stages of fabrication, use, and end-of-life options. In this article, we show that these models can be represented as process flow diagrams or as matrices of process interactions. In either representation, the inventory of environmental emissions and resources used is comparable, provided the process models are proportional in nature (any increase in product output produces a corresponding environmental burden). Matrix representations are advantageous if application cost, feedback flow, or speed of analysis is important. They are also useful in conjunction with comprehensive, general equilibrium models in which the system boundary of the problem (e.g., an LCA of a product) being analyzed is on the level of the national economy.

Life-cycle assessment (LCA) is an important tool used in pollution prevention and green design efforts. Selection of product design, materials, processes, reuse or recycle strategies, and final disposal options requires careful examination of energy and resource consumption as well as environmental discharges associated with each prevention or design alternative. To accomplish this task, LCA models have been developed and software products are available. The International Organization for Standardization (ISO) 14000 international standards for environmental management systems are being developed to formalize the LCA method components (*1*-*3*). Efforts within the United States to develop LCA methodology are being led by the Society for Environmental Toxicology and Chemistry (SETAC) and EPA.

The SETAC-EPA LCA approach focuses first on manufacturing processes (such as the manufacture of paper drinking cups), estimating fuels consumed, other resources used, and the amount of each waste discharged into the environment. The procedure then estimates the resources consumed and environmental discharges produced by the most important upstream suppliers (in the paper cup example, these would include paper mills, pulp mills, and logging operations) and downstream activities (recycling and disposal).

Because of the difficulty in estimating resource consumption and environmental discharges produced by processes associated with the life cycle of a product, the scope of a SETAC-EPA LCA analysis is limited (simplified) by drawing an ad hoc system boundary that excludes all but a few upstream and downstream processes (Figure 1). Consider a hypothetical case in which steel-reinforced concrete is required for constructing 1 kilometer (km) of roadway pavement (Figure 2). The steel-reinforced concrete material costs $150,000, based on a cost of $104,000 for 3680 metric tons (t) of concrete and $46,000 for 78 t of steel. In this example analysis, only one environmental output will be examined, the generation of hazardous waste regulated under Subtitle C of the Resource Conservation and Recovery Act (RCRA) (*4*). The Supporting Information to this article (see p. 190A) provides a more complete analysis, based on use of a full economic input-output (EIO) model of the United States and Toxics Release Inventory (TRI) emissions.
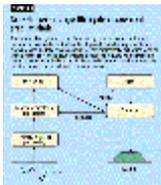

Figure 1: Generic, seven-stage life-cycle assessment product chain
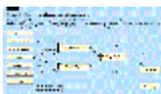
Figure 2: Life cycle of a steel-reinforced concrete component

A simplified analysis of each process stage associated with the steel-reinforced concrete involves developing a process model that indicates required inputs (such as the 78 t of reinforcing steel) and environmental outputs (such as the generated hazardous waste). In the example considered, the amount of desired steel-reinforced concrete product is determined, and required material inputs are traced back through the diagrammed hierarchy of 10 process models for transportation; aggregates, coal, and iron and ferroalloy ores mining; lime; electricity; chemical additives; and cement, concrete, and iron and steel production (Figure 2).

Alternatively, the LCA for steel-reinforced concrete could be represented as a 10 x 10 matrix of direct process stage interactions (Table 1). Only 12 cells in the matrix have

nonzero entries. The other 88 cells in the matrix may (as in a more comprehensive scenario) have nonzero values in them, but as is typical in a simplified analysis, they are ignored or not quantified because they are either trivial or difficult to establish. However, it is clear that steel, for example, is used in aggregates, and iron and ferroalloy ores mining in cement and even in steel production itself.

Table 1: Process model requirements matrix for steel-reinforced concrete

Data entries in the example matrix are expressed in dollar values but can also be expressed in a variety of other units (Table 1). Entries in the concrete production column could be expressed as the number of metric tons of aggregate and cement required for producing a metric ton of concrete. However, not all outputs--for example, electricity generation--are easily expressed in mass units. Valuation in monetary units provides consistency, and conversion to mass or energy can be done using average prices.

The direct supplier process inputs vector for steel-reinforced concrete production, $\mathbf{X}_{\text{direct suppliers}}$, can be obtained by multiplying the matrix $(\mathbf{I} + \mathbf{D})$ by the vector of required outputs of steel-reinforced concrete ingredients:

$$\mathbf{X}_{\text{direct suppliers}} = (\mathbf{I} + \mathbf{D})\mathbf{F} \quad (1)$$

The elements of $\mathbf{X}_{\text{direct suppliers}}$ are the direct supplier inputs to produce steel-reinforced concrete. $\mathbf{I}$ is an identity matrix (to account for the output of the concrete production stage itself), $\mathbf{D}$ is the direct requirements matrix shown in Table 1, and $\mathbf{F}$ is a vector of desired output. The calculation of direct supplier output is shown in Box 1.

Box 1: Process costs for steel-reinforced concrete

More generally, an LCA should take into account the entire supply chain for a product, including indirect suppliers--suppliers to a supplier. In Figure 2, only direct supplier inputs to the concrete and reinforcing steel production processes are indicated, so the supply chain is only one level deep. The second-level supplier requirements could be calculated as the multiplication $\mathbf{DDF}$, but in some cases, a third or fourth level of supply also exists, as shown below. Allowing for added levels of supplier interactions, the total output for the various process stages illustrated in Figure 2 can be calculated as

$$\mathbf{X} = (\mathbf{I} + \mathbf{D} + \mathbf{DD} + \mathbf{DDD} + . . .)\mathbf{F} \quad (2)$$

where $\mathbf{X}$ now takes into account all supplier input levels, $\mathbf{I}$ is the identity matrix, $\mathbf{D}$ is the requirements matrix shown in Table 1, and $\mathbf{F}$ is the vector representing the desired final demand (of reinforced steel and concrete in this case). The supplier requirements series $(\mathbf{I} + \mathbf{D} + \mathbf{DD} + \mathbf{DDD} + . . .)$ is equal to $(\mathbf{I} - \mathbf{D})^{-1}$, so the total input, including the influences of all direct and indirect suppliers ([5]), is

$$\mathbf{X} = (\mathbf{I} - \mathbf{D})^{-1} \mathbf{F} \quad (3)$$

In the simple case, illustrated in Figure 2 and indicated in Table 1, in which only one level of suppliers exists, application of this general solution gives the same result as is obtained from Equation 1, the direct-input analysis (Box 1).

Environmental output calculations

Once the economic output for each process stage is calculated, a vector of environmental outputs can be obtained by multiplying the economic output at each stage by the environmental impact per dollar of output:

$$\mathbf{B_i} = \mathbf{R_i X} = \mathbf{R_i} \, (\mathbf{I} - \mathbf{D})^{-1} \, \mathbf{F} \ (4)$$

$\mathbf{B}$ is the vector of environmental outputs, the subscript $_\mathbf{i}$ denotes the type of burden (including RCRA Subtitle C hazardous wastes and TRI emissions), and $\mathbf{R_i}$ is a matrix that has diagonal elements representing the environmental impact per dollar of output for each process (see Box 2). A variety of environmental burdens might be included in this calculation. Analyses have been performed that include resource inputs (electricity, fuels, ores, and fertilizers) and environmental outputs (toxic emissions by media, hazardous waste generation and management, conventional air pollutant emissions, global warming potential, and ozone-depleting substances) (*6*-*8*).

[Box 2: Environmental burden of steel-reinforced concrete](#)

Some cautions concerning these analysis procedures are warranted. These calculations assume proportionality in environmental impacts; for example, a 20% increase in output of steel-reinforced concrete is assumed to increase environmental burdens by 20%. Such a linear proportionality assumption could be sufficiently accurate even if the underlying effects are nonlinear, but for greater accuracy, an analyst should try to estimate the true environmental effects for anticipated changes in output. In some cases, the best available estimate still might be a linear extrapolation.

Another problem can arise because the simple life-cycle model depicted in Figure 2 does not capture all the environmental consequences of fabricating a steel-reinforced concrete component. Other materials, such as water and formwork, are used along with construction equipment and energy. The selection of boundaries, typically a simplification of the problem, reflects conventional practices and assumes neglected inputs are unimportant. In conducting a SETAC-EPA LCA, the analyst may draw a system boundary that omits many environmental outputs or life-cycle stages from the assessment and consequently may be expected to underestimate environmental effects (*9*, *10*).

Analysts should be extremely cautious in making such assumptions. Environmental impacts can vary significantly from process to process and from industry to industry. For example, the mass of toxic emissions per dollar of output varies by a factor of 100,000 across U.S. industrial sectors and chemicals (*11*, *12*). Small dollar or mass inputs from a particular sector or process may still contribute major portions of the calculated aggregated environmental impact associated with production of a particular product.

Because this is possible, critics might disagree with the chosen boundaries and refuse to accept the results of a particular analysis. When comparing the relative desirability of products, changing the system boundaries in some instances can lead to a conclusion that a different product, process, or material is environmentally preferable to the one originally identified.

A more facile and transparent approach is desirable. Even when there is agreement about system boundaries, the SETAC-EPA LCA methodology is time-consuming and expensive to apply because resource input and environmental discharge data have to be estimated for each of the processes included in the model of the life cycle of a product. Further confounding applications, manufacturers frequently treat gathered data as confidential information and prefer not to make them publicly available. Analyses that are based on the use of such data are controversial--having no way to validate data used in these analyses, people refuse to accept the reliability of the analysis.

An economy-wide LCA approach

A methodology based on EIO and process modeling, in which the system boundary includes the entire economy, may be a preferable alternative to the SETAC-EPA LCA, in which the system boundary that defines the relevant processes is set arbitrarily. For modeling the interdependencies in producing goods and services in the economy, Leontief proposed a general equilibrium model that requires specifying the inputs that any sector of the economy needs from all other sectors to produce a unit of output (*13*). His model is based on a simplifying assumption that increasing the output of goods and services from any sector requires a proportional increase in each input received from all other sectors. The resulting EIO matrix has presently been estimated for developed nations and many industrializing economies. Updated input-output models of this nature and supporting data are regularly established for the entire U.S. economy. The 1987 EIO matrices for the United States divide the economy into 519 commodity sectors (*11*). The general format of the transactions matrix for the basic EIO model is indicated in Table 2, and Table 3 illustrates the total requirements matrix for the steel-reinforced concrete product example. With an input-output model in this form, an analyst can use Equation 4 to consider the environmental effects throughout the economy that result from a particular output change.

[Table 2: Economic input--output transaction table structure](#)

[Table 3: Total requirements matrix for steel-reinforced concrete product](#)

Analogous to using a matrix to represent process models of life-cycle stages, an EIO model can be represented as a process chain in the same way as is shown in Figures 1 and 2. However, each box in the chain would then represent an economic sector rather than a specific process. Because this EIO model is comprehensive for the entire economy, the process chain diagram would include connections among all sectors. Using 519 commodity sectors, such as are contained in the most detailed EIO model estimated by the U.S. Department of Commerce, would result in a hopelessly complex diagram.

In seeking to determine the environmental effects of a product, the choice of criteria for drawing boundaries is essential. Based on an analysis of all 519 sectors of the U.S. economy, using the steel-reinforced concrete pavement example, the total incremental demand created by production of $150,000 of reinforced concrete needed to make 1 km of pavement is $326,000, significantly more than the $213,000 calculated from the 10-sector model shown in Figure 2. Table 4 indicates major economic sector contributors for the steel-reinforced concrete example. The full table, found in Supporting Information, indicates, in decreasing order, the demand generated in all 519 sectors of the economy.

Table 4: Major sector contributors to steel-reinforced

Indirect interactions between suppliers can be important--production of cement requires steel for the associated manufacturing plant and equipment, and steel mills typically use concrete for their initial construction. Although indirect demands may be small individually, taken as a whole they can be significant, because they are likely to be numerous. These demands are omitted in the LCA suggested in Figure 2 and in Table 1, although even among the 10 sectors shown in Table 1, the indirect interactions are substantial. Moreover, economic sectors also purchase some of their own individual products. With a matrix representation of a process supply chain, indirect economic impacts can be included by applying Equation 3. Table 3 gives a complete listing of direct and indirect interactions among the 10 processes in the simplified LCA model, based on the cash flows of economic sectors (*11*). The full 519 x 519 total requirements matrix of the entire U.S. economy is not presented in this article, but the table found in Supporting Information includes all such economic interactions. Note that there are no zero elements in Table 3, indicating that each sector directly or indirectly requires input from all other sectors, including additional demand from the sector itself. For example, the steel sector itself purchases steel, as indicated in Table 3, where $1 of steel demand actually requires $1.17 of steel production, and $1 of concrete demand generates $1.01 in the concrete production sector. Tracking all the indirect contributions would be impossible in a conventional stage-by-stage LCA, because cycles among stages would continue indefinitely.

EIO tables greatly facilitate a first-order approximation of the economy-wide environmental impacts of a production decision; and in the economy-wide treatment, the extent of hazardous waste and emissions generation is revealed more fully. The table of data found in Supporting Information also presents a tabulation of RCRA Subtitle C hazardous waste generated, managed, and shipped, and the TRI emissions produced in all sectors as a result of producing $150,000 of reinforced concrete for 1 km of pavement. Inspection of this supplemental table indicates that other sectors, not included in the SETAC-EPA LCA process model illustrated in Figure 2, have significant environmental impacts.

Indirect environmental effects associated with these sector interactions can be estimated by applying Equation 4. The SETAC-EPA LCA process model would typically include only the environmental effects of a few suppliers in an LCA, because inclusion of all the direct and indirect suppliers is time-consuming and expensive. The top waste-generating

economic sectors for the steel-reinforced concrete example are shown in Table 5. In Supporting Information, wastes generated by the full 519 sectors are indicated. The amount of waste generated is considerably more than the 2760 kilograms (kg) calculated from considering only the 10-sector process model shown in Figure 2. Based on data reported in the Supporting Information table, in association with $104,000 of concrete and $46,000 of steel reinforcement, 8430 kg of RCRA Subtitle C hazardous waste would be generated in the entire economy. Examination of the results presented in Box 2 and in Table 5 reveals that the chemicals and chemical preparations sector (other than the ones accounted for in Figure 2) and the petroleum refining sector account for more than 50% of total RCRA hazardous waste generation. Note that in Table 5 the RCRA hazardous waste generation effect of the steel reinforcing production is actually 2300 kg. This is more than the 1950 kg waste generation figure estimated from the 10-sector economic model. The difference is accounted for by the steel required to produce steel, which is not included in the simple process model. Quantification of many other environmental effects, in addition to RCRA Subtitle C hazardous waste generation and the TRI emissions reported in Supporting Information, is also possible using the economy-wide EIO model.

Table 5: Hazardous waste generated in producing

Analysis of methodological relevance

The process chain SETAC-EPA LCA and EIO LCA models can be represented using similar matrix or process model representations, as long as linear proportionality in the production relationships is assumed. The SETAC-EPA LCA approach is problem specific and tailors process models to the problem, whereas the EIO LCA model relies on a general equilibrium model of an entire economy.

The two approaches can be integrated to provide a more accurate or cost-effective LCA or to provide alternative estimates for comparison purposes. In particular, the EIO LCA can be applied for the materials extraction and manufacturing-stage assessments to advantageously use an economy-wide boundary; and to advantageously use its focus on specific processes, the SETAC-EPA LCA approach can function in product-use and end-of-life phase assessments. For example, the EIO LCA is effective in assessing environmental effects of materials extraction and manufacturing of concrete and steel for steel-reinforced concrete pavements. In concert with this treatment, the SETAC-EPA LCA model can provide information about the effects of the construction stage (such as particulate emissions), the environmental effects of the use stage (such as particulate emissions as a result of deterioration), and the environmental effects of the end-of-life stage (such as recycling of concrete for backfill) of the pavement.

The methods provide alternative ways, and therefore broadened opportunities, to estimate environmental effects. The EIO LCA provides an assessment on the level of the U.S. economy at a relatively low cost, and the SETAC-EPA LCA process model examines the effects of specific processes through reliance on data collection and literature research. For example, the EIO LCA gives results for sugar as a generic agricultural product, whereas the SETAC-EPA LCA process model approach can focus specifically on

sugarcane. The EIO LCA model might be used to indicate which particular process links require detailed modeling. It can direct attention to a particular environmental problem identified at the national level (such as use of ozone-depleting substances as solvents), which then may warrant detailed process examination and additional time and money input into the analysis (such as opportunities for substitution of environmentally acceptable solvents).

The EIO approach has limitations. Even with 519 economic sectors represented, the amount of disaggregation may be insufficient for the desired level of analysis. EIO LCA models include sectors of the economy rather than simple processes. The sectors may be too heterogeneous to correctly reflect a particular process. However, the sector model does have the advantage of including effects attributable to the influences of many indirect suppliers, which can be overlooked in process models. Another limitation is that the basic EIO LCA model can be used to reflect fabrication of a product or process but not the environmental impacts arising from use or disposal. To overcome these limitations, LCA analysts might wish to augment an EIO requirements table with independently estimated process models represented as new rows and columns in the requirements table (_7_). Alternatively, particular sectors could be disaggregated to reflect specific processes or products.

The EIO LCA approach also has several advantages. A comprehensive model of the economy is used so that analysts need not draw arbitrary boundaries. Analyses can be performed rapidly and inexpensively. This property is extremely important in design applications in which approximate but rapid results are needed. Analyses are transparent in that only publicly available data and standard calculations are used. Indirect and feedback relationships among the different processes and economic sectors can be included directly. Process models can be added when data become available or analysis requires finer detail. The EIO approach offers an opportunity to compare different LCA strategies for analyzing particular supply chains, improving the confidence in results, or helping to identify errors (_6_, _14_).

Matrix representation permits the use of publicly available, standard data sources, such as the national sector-based, economic input-output (EIO) tables produced by the U.S. Department of Commerce. EIO models allow for a comprehensive assessment of the environmental effects of a production decision. A typical, less comprehensive process flow model analysis--for example, the analysis of the impacts of producing steel-reinforced concrete required for paving 1 kilometer (km) of road surface--accounts for only two-thirds of the economy-wide material and energy inputs in monetary terms and neglects two-thirds of the economy-wide amount of the Resource Conservation and Recovery Act (RCRA) hazardous wastes generated.

Several outstanding issues need continued attention: The accuracy, completeness, and timeliness of data required for assessment of environmental impacts of particular industries and processes must be assured. More generally, methods of validating LCA estimates must be established, and ways should be sought to extend EIO models to account for regional differences (at the state or county level) and to include international

effects.

Supporting Information

Supporting Information cited in this article appears following these pages in the microfilm edition of this volume of the journal. Photocopies of Supporting Information from this paper or microfiche (105 x 148 mm, 24 x reduction, negatives) may be obtained from the Microforms Office, American Chemical Society, 1155 16th St., NW, Washington, DC 20036. Full bibliographic citation (journal, number, and issue number) and prepayment, check, or money order are required. The cost of SI on microfiche is always $12 and $13 (foreign). Canadian residents should add 7% GST. The cost of photocopied SI varies. It is $12 for the first 3 pages of SI and then an additional $1.50 per page with $2 added for the foreign cost. Supporting Information is also available via the World Wide Web at URL http://www.chemcenter.org. Users should select Electronic Publications and then *Environmental Science & Technology* under Electronic Editions. Detailed instructions for using this service, along with a description of the file formats, are available at this site. To download the Supporting Information, enter the journal subscription number from your mailing label. For additional information on electronic access, send electronic mail to si-help@acs.org or phone (202) 872-6333.

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