Case study: Economic Input-Output Life Cycle Assessment of Asphalt versus Steel Reinforced Concrete for Pavement Construction.

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Goals of This Assignment

This assignment will show the use of life cycle assessment though a specific case study exercise. The case study introduces environmental life cycle assessment (LCA), explains a specific method of conducting LCAs (the EIOLCA approach), and shows how to carry out an EIOLCA on the world wide web in a step-by-step approach.
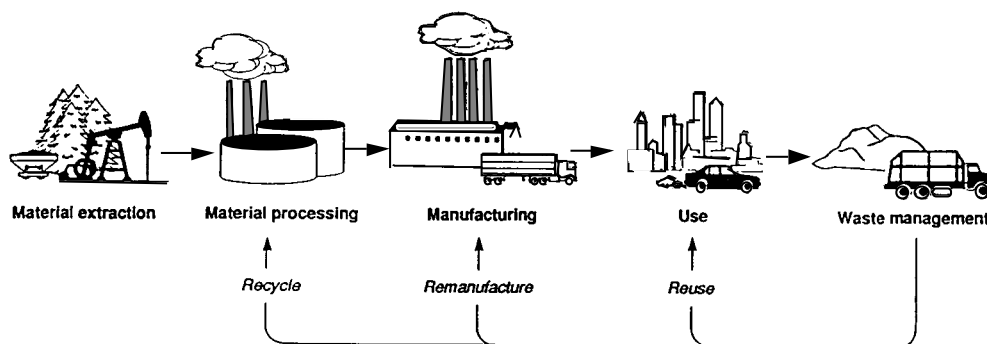
The assignment should be used in class to complement class instruction on LCA and different methods of LCA. Although the case study includes a step-by-step demonstration of using the EIOLCA module, the students are left to complete the exercise on their own and to discuss the results and the pros and cons of using the model.

Overview of LCA and EIOLCA

Green Design and pollution prevention are proactive strategies to minimize the environmental burdens associated with a product or process without compromising functionality. Life cycle assessment (LCA) is an important tool used in pollution prevention and green design efforts. Selection of product design, materials, processes, reuse or recycling 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.

LCA involves evaluating the environmental effects of a product, process, or activity holistically, by looking at the entire life cycle of the product or process from raw materials extraction through consumer use (Figure 1). Coca Cola was one of the first corporations to attempt LCA when the company analyzed the environmental impacts of beverage containers in the 1960s. LCA criteria are beginning to find their way into environmental labeling schemes such as Germany's Blue Angel and the ISO 14000 environmental management standards (www.iso.ch). Simplified LCAs even pop up in popular magazines; for example, Consumer Reports occasionally comments on the environmental impacts of different product packaging types and chemicals.

Figure 1. Stages of a product life cycle (From *Green Products by Design: Choices for a Cleaner Environment*. U.S. Congress, Office of Technology Assessment, OTA-E-541).

Material extraction   Material processing   Manufacturing   Use   Waste management

Recycle   Remanufacture   Reuse

The use of LCAs as part of labeling systems and management criteria has led to a heated debate about just what criteria should be measured and how impacts should be compared. A number of efforts involving industry, government agencies, and universities are focusing on standardizing the analyses so that LCAs carried out by different organizations are comparable. LCAs have been criticized for a number of reasons:

- Environmental effects for all life-cycle stages are not known
- It is difficult to compare different types of effects, such as species extinction versus cancer incidence.
- The amount of data required to analyze even simple products is enormous; the typical cost for a detailed LCA may exceed $200,000.
- Data gathering is difficult as many of the life cycle stages involve proprietary processes
- It is difficult to know where to draw the boundary around the analysis - should raw materials extraction be included? What about the life cycle impacts of the equipment used in the raw materials extraction? What about the environmental impacts of the detergent used to wash the clothes of the people mining the raw materials!

Despite the drawbacks, LCA can show the major environmental problems of a material, product, or process. The act of doing the assessment builds awareness about environmental impacts and focuses improvement efforts. This has led companies, such as AT&T, to develop internal LCA tools for their product lines (Graedel and Allenby, 1995) and Government agencies, such as the EPA, to provide generic guidelines for conducting LCAs (USEPA, 1993).

Most current LCA techniques are modifications of the approach developed by the Society for Environmental Toxicology and Chemistry (SETAC). Practical use of the SETAC approach involves drawing a boundary that limits consideration to a few producers of interest in the chain from raw materials to consumers. Researchers at Carnegie Mellon have found that limiting the analysis in this way may lead to consideration of only a fraction of the total environmental discharges associated with the product or process. They have developed an approach based on models of industrial activity (input-output tables) and pollution discharge data (such as TRI data) (Cobas et al, 1995; Lave et al., 1995; Lave et al, 1996; Hendrickson et al, 1998). The resulting

software tool, called Economic Input-Output LCA or EIOLCA allows for economy-wide LCAs at a fairly coarse (aggregate) scale.

The input-output analysis technique that forms the basis of the model was developed by Wassily Leontief (for which he received a Nobel Prize in 1973) [Leontief, 1970, 1986]. Leontief assumed that the complicated interactions within an economy can be approximated by proportionality relationships. For example, if 90,000 tons of steel are required to make 100,000 cars, 180,000 tons will be required for 200,000 cars. One might think of an input-output model as a first order Taylor series approximation to the actual, more complicated relationships. For small movements around observed data, the input-output model will provide a good approximation.

Input-output analysis has been used extensively for planning in the USA and throughout the world. Like the United States, many countries collect and publish input-output tables for their economies. The tables are used to calculate the resources and supply chain requirements required to support an increase in the demand for output of specific sectors like automobiles or food. The resulting estimates show the indirect increase in production, both for automobiles and for all the other sectors that supply products, directly or indirectly, to the automobile industry. In general, each sector contributes directly or indirectly to every other sector. For example, an expansion in the automobile production would require steel, electricity, petroleum, plastics and even some automobiles for transport. The data underlying an input-output table characterize these inputs for every sector.

Researchers at Carnegie Mellon have used the U.S. Department of Commerce input-output tables for the US to develop an economy-wide LCA technique by linking the economic input-output tables with environmental databases (conventional pollutants, TRI, energy use, ore use, fertilizer use, global warming potential, and ozone depleting potential, etc.). The method is called Economic Input-Output Life Cycle Assessment, or EIOLCA.

EIOLCA MODEL STEPS AND CALCULATIONS

To use the EIOLCA model, the user must first determine which life cycle stage is under consideration and how best to determine the dollar value of the resources required for the product, process or service in the life cycle stage of question. For example, if the user is interested in the manufacturing stage, they would need to know the approximate dollar value for each of the materials (steel, oil, electricity, etc.) required for manufacturing. If the user was interested in looking at the environmental implications of product use, they would need to determine the dollar values of the inputs required for lifetime use (for example fuel requirements, electricity requirements, paper requirements etc.). The resulting environmental discharge and resource use results would then need to be summed to arrive at a "manufacturing and use" LCA.

The EIOLCA mathematical analysis occurs in several stages. First, the model is started by specifying an increase or decrease in demand for a sector. For example, switching from steel to aluminum for some automobile components would be represented by an increase in aluminum demand and a decrease in the demand for steel output. Second, the economic input-output model is used to estimate both direct and indirect changes in output throughout the economy for each sector (if necessary, published input-output tables are augmented by adding more sectors or disaggregating existing sectors for this purpose). Third, the environmental discharges of the changes are assessed by multiplying the economy-wide output changes by the average environmental discharges associated with unit output of each sector. The overall environmental impact is characterized by this vector of discharges and by selected summary indices. These steps are presented in a mathematical form below.

The EIOLCA model first calculates the change in all commodity demands due to an increase in final demand of a specific sector. If X is the change in total commodity output (a 500 entry vector in dollars), I is an identity matrix (to include the output of the of the specific sector), D is the requirements matrix (a 500 by 500 matrix showing the purchases from other commodity sectors for the production of a specific sector), and F is a vector representing the desired final demand. Then the total output including indirect suppliers is:

$X = (I-D)^{-1}F$

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

$B_i = R_iX = R_i(I-D)^{-1}F$

where B_i is the vector of environmental burdens (such as toxic emissions or electricity use), and R_i is a matrix with diagonal elements representing the impact per dollar of output for each stage. A large variety of environmental burdens can be included in this calculation.

The data in EIOLCA is developed from a variety of public databases and assembled for various commodity sectors. For the most part, the data is self reported and is subject to measurement error and reporting requirement gaps. Some of the major data sources include:
- The commodity/commodity input-output matrix of the US economy as developed by the US Department of Commerce.
- Electric use including manufacturing and mining sectors developed from the Census of Manufacturers. Service sector electricity use is estimated using the detailed IO workfile and average electricity prices for these sectors.
- Fuel and ore use is calculated from commodity purchases (contained in the IO workfiles) and average prices.
- Fertilizer use is calculated from commodity purchases (contained in the IO workfiles) and average prices.
- Toxic releases are derived from the US EPA's Toxics Release Inventory (TRI) and value of shipments from the 1995 Department of Commerce Annual Survey of Manufacturers.
- RCRA (Resource Conservation and Recovery Act) Subtitle C hazardous waste generation, management and shipment were derived from the biannual US EPA report (EPA 1993b).

The model is a simple, rapid, and relatively noncontroversial way of estimating the supply chain implications for a change in demand for a particular product or service. The EIOLCA approach has been used to examine the environmental impacts of various

industrial sectors (Cobas et al, 1995, Lave et al, 1995, Lave et al, 1998), automobile use (MacLean and Lave, 1998), automobile components (Joshi, 1997) and construction materials (Horvath and Hendrickson, 1998a, b; Hendrickson and Horvath, 1998).

The EIOLCA tool has advantages over other LCA techniques:

- EIOLCAs can be used to examine the total direct and indirect economy-wide effects (effects of suppliers) on emissions and energy consumption resulting from changes in production.
- The EIOLCA model uses the entire US economy as the boundary for the analysis.
- The approach highlights priority areas for reduction in environmental impacts.
- Initial EIOLCAs can be carried out at a fraction of the cost and time associated with SETAC-LCAs.
- The EIOLCA can be used in conjunction with current SETAC approaches, where the SETAC approach is used to analyze specific products and processes in detail and the EIOLCA explores the indirect economy-wide effects of changes in product mix.
- The LCA is calculated by a transparent, computer-based tool that is easily implemented as part of green design efforts.
- The LCA has underlying data bases accessible by all environmental stakeholders.
- The method provides some environmental information for every commodity in the U.S. economy.
- The method allows for sensitivity analyses and scenario planning.
- The method is complete and the software is available either through the Green Design Initiative at Carnegie Mellon or via the World Wide Web at www.eiolca.net.
- Results are reproducible by environmental stakeholders

The EIOLCA approach also has limitations. Even with 500 economic sectors, the amount of disaggregation may be insufficient for the desired level of analysis. EIOLCA models include sectors of the economy rather than specific processes. Detailed analysis of the environmental impacts of the activities of the individual members of the supply chain will require more traditional SETAC-LCA techniques. The use and disposal phases of certain products may be too difficult to analyze with EIOLCA. In addition, the data in the model may reflect past practices, and use if imports are treated as if they are U.S. products.

Description of the EIOLCA Case Study

Asphalt vs. Steel Reinforced Concrete for Pavement Construction.

Construction is a significant portion of US economic activity. Construction and infrastructure development account for a disproportionate share of resource use – understanding the resource use and emissions associated with construction related activities is an important component of developing sustainable industrial systems. Hendrickson and Horvath (98) have used the EIOLCA method to examine the resource inputs and emissions for aggregate US construction sectors and found that construction accounts for a disproportionate share of several mineral and pollution emission categories.
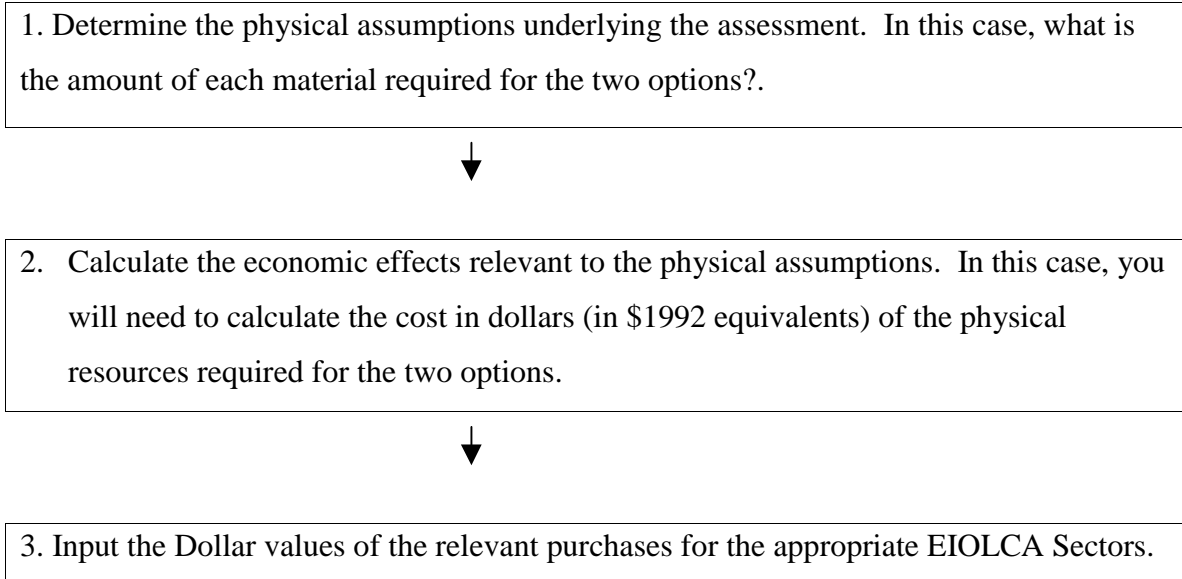
Horvath and Hendrickson (98b) used the EIOLCA method to do specific comparisons of the environmental implications of asphalt and steel-reinforced concrete pavements. Asphalt and concrete (often reinforced with steel) are the most common materials used in pavement construction. They compared the resource requirements and emissions associated with constructing a new 1km-long pavement section composed of either asphalt or concrete. Specific details about the roadway designs are provided in the source article (Horvath and Hendrickson, 98b). The resource inputs evaluated included consumption of electricity, fuels, ores, and fertilizers. In addition, the EIOLCA method allowed for the identification of inputs not directly related to pavement material manufacturing such as fertilizer demand. In this case, fertilizer consumption occurs with some of the agricultural suppliers of some of the direct suppliers to the asphalt and concrete sectors. Environmental effects include toxic chemical discharges to air, water, land, and underground, and transfers to off-site treatment plants, ozone depletion potential of chemical releases, hazardous waste generation, and conventional pollutant releases to air. The environmental effects of both direct suppliers (such as the cement industry) and indirect suppliers (such as the agricultural sector) are included in the analysis. This comparison forms the basis of the analysis shown below.

The EIOLCA pavement comparison analysis.

In this assessment you will use the EIOLCA software (www.EIOLCA.net) to compare the environmental impacts associated with manufacturing each type of pavement.

Carrying out an EIOLCA analysis requires that you make a series of assumptions – both physical and economic (see figure 2).

Figure 2. Schematic demonstrating the steps required to conduct the EIOLCA.

1. Determine the physical assumptions underlying the assessment. In this case, what is the amount of each material required for the two options?.

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2. Calculate the economic effects relevant to the physical assumptions. In this case, you will need to calculate the cost in dollars (in $1992 equivalents) of the physical resources required for the two options.

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3. Input the Dollar values of the relevant purchases for the appropriate EIOLCA Sectors.

To complete this sequence of activities for the pavement example you need to do the following:

1) Determine the amount of materials required for each paving type for pavements of equivalent functionality e.g. 1 km of pavement.

In this case, we are comparing pavements of 1km long, 7.2m wide on 15cm cement treated sub-bases. Equivalent designs of this type would require differing amounts of the two materials being considered. The asphalt pavement would need to be 30 cm thick which would require **5018**mt of asphalt. The steel-reinforced concrete (SRC) pavement would need to be 22cm thick requiring **3680**mt of concrete and **77**mt of steel rebars.

2) *Calculate the dollar costs for the materials. NOTE the EIOLCA software only accepts inputs in the form of dollar amounts for materials . The values should be adjusted to 1992 dollars as the model is the 1992 Department of Commerce model.*

In 1992,

5018mt of asphalt cost: $145,500

3680mt of concrete cost: $106,700

77mt of steel rebars cost: $23,400

Note that price indices can be used to0 convert current dollars into 1992 dollars.

3) *The name of the economic sector responsible for producing the material, or appropriate keywords to allow the EIOLCA software to search for the appropriate sector.*

In this example, a search on the word "asphalt" yields the following commodity sector choices:

Asphalt felts and coatings

Asphalt paving mixtures and blocks

Paper and paperboard mills

Nonmetallic mineral services and miscellaneous

Asbestos products

Petroleum mining

Construction machinery and equipment

Paints and allied products

The most appropriate commodity sector is **asphalt paving mixtures and blocks**. This can be determined by clicking on the "view descriptions of matched sectors" button which shows detailed lists of products included in each sector.

Similarly, a search of the word 'concrete' gives a list of choices including **"ready mixed concrete"**. This appears to be the best match for the type of concrete in pavement. A

search for "steel" reveals a list of choices which **"blast furnaces and steel mills"** appearing to be the most appropriate.

Note: the actual sector you use to approximate your material or product will depend somewhat on your knowledge of the manufacturing process required for your material.

Now that we know the dollar amounts of the materials we need for our paving application and we know the names of the sectors which best approximate the manufacturing activities required for the material we can do the EIOLCA analysis. The results will provide an understanding of the economic and environmental issues associated with the manufacturing stage of the material[1].

Once you know the names of the sectors you will be using, click on the appropriate name to start the analysis and enter the dollar purchase requirement for that that sector ($145,500 demand for the asphalt pavings and blocks sector for example). You also need to specify the particular data results you would like displayed. There are many options as described below. You should go through each data screen for each purchase/demand to familiarize yourself with each set of data. Some examples are discussed in Table 1.

You need to complete the assessment by doing a similar analyses for the concrete paving and comparing the results. Sort by each column and print in order to have the column totals and a listing of the dominant contributors for each input or output. In order to check your analyses, in the asphalt example the column totals for "Economic Impacts", "Energy", SO2, and "iron" are $0.35million, 6.76 terajoules, 1.08mt, and 1.92 mt respectively.

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[1] Note, if we wanted to do a similar assessment of the use phase of a product or process, we would proceed in a similar way. First, we would estimate the resources required for use (e.g. energy, transportation etc) and then estimate the economic and environmental issues associated with manufacturing these materials. We would then sum the results.

Remember to add the results of the concrete and steel analyses to get a 'reinforced concrete" result.

Specific questions related to the case are:

1) Which material seems to have the lowest impact on the environment?
2) What issues complicate the assessment?
3) How would you try to include potential product recycling in the assessment?
4) How would your assessment change if one pavement material lasted longer than the other?

Additional assignment related to the use of EIOLCA

The Carnegie Mellon University green design educational web pages (www.ce.cmu.edu/green/Design) also contain a case study entitled 'Rechargeable Battery Management and Recycling".   Student assignment 8 in this case study involves using EIOLCA to conduct a life cycle assessment of differing battery types. The physical and economic assumptions and required for the assessment are included in the assignment along with a series of questions related to the assignment.

Table 1. Summary of the EIOLCA.net output pages and their interpretation

Economic/Energy/ ODP	This data output page shows the total economic activity generated throughout the 500 sector supply chain as a result of increasing demand in a sector. In this example, $145,000 demand in the asphalt pavings and blocks sector results in a total economic activity throughout the US economy of $349,000. While entering the appropriate demands for concrete and steel results in a total economic activity of $289,000 ($233,000 from concrete, $56,000 from steel). The screen also shows the energy used to produce this economic activity along with the Ozone Depleting Potential of the emissions resulting from the economic activity. By sorting the screens, it is possible to determine which sectors account for the largest portion of the data in question. In this example, it can be seen that the "crude petroleum and natural gas" sector is responsible for almost 50% of the energy required to meet our requirement for asphalt (the asphalt sector is only 4th on the list). The asphalt sector itself is however responsible for the largest share of electricity use.
Conventional Pollutants	This data output page lists the SO2, CO, NOx, Lead, VOC, and PM10 resulting for the economic transactions throughout the entire 500 sector supply chain. Again the results can be sorted to determine which sectors are predominantly contributing to the emissions. Using the asphalt purchase as an example again, it can be seen that a number of sectors contribute to the release of NOx (remember to sort by NOX to see the specific results), while the asphalt sector itself is the largest contributor of CO emissions.
Global Warming gases	This output page shows the emissions of various gases associated with global warming. Again, the data can be sorted as required to determine which sectors are predominantly responsible for emissions of a particular pollutant.
Fertilizers	This output page shows the amounts of various common fertilizers used throughout the supply chain in the production of the commodity in question. This information is important in estimating potential ecosystem impacts of sector activities and to understand the extent of the input requirements for production.
Fuels	This output shows the amounts of various fuels (coals, petroleum, LPG, aviation fuel etc.) required throughout the supply chain for the production of the commodity. This is important in understanding the resource input requirements for production.
Ores	This output table shows the amounts of various ores (iron, copper, bauxite, for example) required for production throughout the supply chain. Again, this information is useful for understanding resource requirements and non-renewable resource depletion.
RCRA Hazardous Wastes	This output shows the reported RCRA (Resource Conservation and Recovery Act) Subtitle C hazardous waste generation, management and shipment was derived from the 1993 biannual EPA report (USEPA 1993b). The output is broken down as RCRA generated, RCRA manag RCRA shipped.
External Costs	External costs are costs (such as the health costs to society resulting from emissions) which are not included in the private costs borne by companies. In the model they are calculated from conventional air pollutant emissions and estimates of pollution damage taken from the economics literature. Detailed information on these values are available upon request. Low medium and high costs are estimated, however, the estimates are based only a small subset of emissions.
TRI by Sector	Toxic releases are derived from the US EPA's 1995 Toxics Release Inventory (TRI) and 1995 value of shipments from the 1995 Department of Commerce Annual Survey of Manufacturers. This output section shows the TRI reported by each Industry sector to highlight industries of concern. The output is broken down according to the TRI reporting protocols into non-point air emissions, water releases etc.
TRI by Chemical	This section shows the most recent TRI reports listed by chemical to show the main chemicals of concern.
CMU-ET by Sector	CMU-ET is a weighting scheme for toxic emissions to account for their relative hazard. It is computed from occupational exposure standards (called threshold limit values). The gross amount of toxic emissions is converted into metric tons of sulfuric acid emissions equivalent (please refer to Horvath et al., 1995 for more details on the method). In this output screen, the CMU-ET values are broken down by sector.
CMU-ET by Chemical	This page shows the CMU-ET values listed by chemical

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