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USING ECONOMIC INPUT-OUTPUT LIFE CYCLE ASSESSMENT TO GUIDE SUSTAINABLE DESIGN

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ABSTRACT
Successful design for the environment (DfE) requires the designer to understand the life cycle impact of design decisions. However, estimating life cycle implications of design choices using traditional process-based life cycle assessment (LCA) is typically too time- and resource-intensive to be practical as part of the design process. We examine the use of economic input-output life cycle assessment (EIO-LCA) as a tool to support sustainable design by helping the designer to quickly determine which aspects of the product dominate its lifetime emissions. Compared to traditional process-based LCA, EIO-LCA produces estimates at a more aggregated level using data on economic transactions and emissions from each sector of the economy. However, EIO-LCA computes full supply chain emissions associated with output from a particular sector in seconds, and for many products these aggregate-level data are sufficient to determine which aspects of the product dominate and to guide sustainable design efforts. We explore two product design examples where a quick scoping exercise with EIO-LCA identifies clear areas of focus for design improvement and innovation.

1. INTRODUCTION
To reduce the environmental impacts of goods and services, design for the environment involves understanding a product's life cycle impacts and then altering its design to reduce the impact, while improving or maintaining acceptable technical and market performance. Life cycle assessment methods can be used to estimate the amount of environmental releases associated with a product's production, distribution, use, and end of life. Often one of these phases is responsible for the lion's share of emissions. For example, automobiles and buildings typically have their largest impact during the use phase through resource consumption and emissions (Hendrickson, 2006). In contrast, the largest impacts for electronics and food products are typically during the production phase, including the supply chain of intermediate products (Hendrickson, 2006).

Traditional LCA methods rely on a series of process models that represent all the various components of the product life cycle and supply chain (Graedel, 2010). Hundreds of distinct process models might be involved in modeling a moderately complex product, requiring considerable time, expertise and expense that are often not available in the design process. Abbreviated or streamlined LCA has been developed to reduce these requirements and make LCA practical to include in the design processes, where speed is essential. In particular, many LCA studies use existing databases of process models, such as ECOINVENT (2011) or BEES (NIST 2000).

In this paper, we describe an existing life cycle assessment model and provide some examples of its use for DfE. The Economic Input-Output Life Cycle Assessment (EIO-LCA) is based upon publically available databases and is available for free use at the website www.eiolca.net (Hendrickson 2006). The EIO-LCA model has the advantages of low cost, rapid use, and a consistent boundary for analysis (consisting of the U.S. economy). However, it is based on fairly aggregate production sectors, so detailed life cycle assessments must use more detailed process-based models. EIO-LCA also has the benefit of capturing emissions from processes far upstream (e.g.: mining) as well as supply chain loops (e.g.: mining is needed to produce steel, but steel is needed in mining) that can be difficult to account for in a process-based approach.

Using both EIO-LCA and process based models is also possible. EIO-LCA can be used to rapidly scope out areas of particular concern for environmental impacts. Results from EIO-LCA and process-based models can be compared, just as alternative process-based database results can be compared.

Also, EIO-LCA can be used to assess some supply chain inputs (such as electricity supply) and process-based models used for other inputs. A discussion of the two approaches and examples of 'hybrid' or combination approaches appears in Hendrickson (2006).

2. THE ECONOMIC INPUT-OUTPUT LIFE CYCLE ASSESSMENT MODEL

Theory and Methodology

The EIO-LCA model is based on government-defined economic sectors and data collected on economic transactions between sectors as well as environmental releases from each sector. The method assumes that there is a linear relation between the economic value of output from a sector and the amount of emissions released from that sector (i.e.: EIO-LCA assumes releases from marginal output equal releases from average output in the sector). The model recognizes that producing output from a sector requires input from other sectors, and the corresponding emissions from each upstream sector can be a substantial portion of overall emissions. For example, grilling a hamburger may create direct emissions from the charcoal used to heat it, but the full supply-chain emissions associated with delivering a grilled hamburger to a consumer also include mining, processing, and transporting the charcoal; raising, slaughtering, processing, and transporting meat; and emissions associated with retail such as refrigeration. Electricity use in each of these processes involves upstream mining, transportation, and combustion of fuels used to generate electricity.

Input-output transactions tables, which track flows of purchases between sectors, are collected by the federal government in the United States (BEA 2011). As developed by Leontief (1970), these transactions can be used to estimate the complete supply chain activity of sector purchases for production of a good or service. Coupled with emissions and resource inputs, the sector purchases can be used to estimate the supply chain environmental impacts of producing a good or service.

The Economic Input-Output (EIO) model works as follows: If X_{ij} represents the annual economic value of goods and services that sector j purchases from sector i and y_i is the final demand for output from sector i -- i.e., the amount of output purchased for consumption, as opposed to purchased by other businesses as supplies for more production -- then the total output x_i from sector i includes final output to consumers plus output sold to other sectors:

$$x_i = y_i + \Sigma_j X_{ij}$$

If we define A_{ij} as the normalized production for each sector, so that $A_{ij} = X_{ij} / x_j$, then

$$x_i = y_i + \Sigma_j A_{ij} x_j$$

In vector notation

$$\mathbf{x} = \mathbf{y} + \mathbf{A}\mathbf{x}$$
$$\mathbf{y} = (\mathbf{I} - \mathbf{A})\mathbf{x}$$
$$\mathbf{x} = (\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$$

This result indicates that knowing only the final demand from each sector **y** and the normalized input-output matrix **A**, one can calculate the total implied production **x** from each sector of the economy. If data are available on a particular emissions release (or other attribute of interest) from each sector of the economy, then a matrix **R** can be compiled to represent various releases (columns) per dollar output from each sector (rows). Total releases **r** associated with a final demand of **y** can then be calculated as:

$$\mathbf{r} = \mathbf{R}^T\mathbf{x} = \mathbf{R}^T(\mathbf{I} - \mathbf{A})^{-1}\mathbf{y}$$

This simple result enables quick estimates of the releases **r** associated with the entire supply chain requirements needed to provide a specific final demand **y**, on average. The equations are based on data in the economy for the year in which the input-output matrix was estimated. The equations can be used to make predictions for marginal changes in output from a particular sector under the following assumptions:

- average output and marginal output are assumed to be sufficiently similar (i.e., the emissions caused by one more unit equals the emissions of the average unit), and
- the marginal change in final output **y** is representative of the product of interest (e.g.: if the product will use electricity from wind energy exclusively, then using the electricity sector, which is dominated by coal, would yield a poor estimate).

Finally, if the researcher has estimates for valuation of externality costs associated with each item in **r** (or, alternatively, if weighting coefficients are available that represent the relative importance of each item in **r**, such as Eco-Indicator 99 (Pre 1999, MHSPE 2000) then the externality costs (or weights) per unit of releases could be compiled into a vector **m** in order to calculate the scalar environmental impact metric m:

$$m = \mathbf{m}^T\mathbf{r}$$

Generally there is wide uncertainty associated with estimates of **m**, so such aggregation should be done only with care, including sensitivity analysis. Researchers often examine specific elements of **r** rather than attempting to aggregate all environmental releases into a single metric.

The overall result is that by collecting data on average economic sector transactions **A** and average sector emissions **R**, it is possible to make quick predictions about the full supply chain emissions associated with a product of interest by representing the product as marginal changes in production from relevant sectors **y**.

Using EIO-LCA to Assess Life Cycle Emissions for a Product

To use the EIO-LCA model to assess life cycle emissions associated with a particular product, the designer represents the product as a set of final demand economic transactions **y** over the product's lifetime. Typically this involves (1) emissions associated with producing the product and delivering it to the user, (2) emissions associated with the use phase, and (3) emissions associated with end of life. Each of these phases is represented as an economic transaction or set of transactions of final demand that represent consumption in that phase, and EIO-LCA automatically accounts for upstream emissions associated with supplying the sectors that produce the final demand. A producer price model is used when prices indicate wholesale value of output from each sector. A purchaser price model, which includes an additional transformation to account for distributional and retail activities and their markup, is used when prices indicate retail purchase price of final demand. We provide several examples in Section 3.

The EIO-LCA model implementation provides estimates of conventional air pollutants, greenhouse gasses, energy use, and toxic releases associated with economic activity in each sector of the economy needed to produce the final output. Determining where to focus design efforts may require use of economic valuation or economic indicators (Hendrickson 2006, NRC 2010), examination of regulatory guidelines, or reference to design objectives. Furthermore, the designer should

- **Ask What Can Be Controlled:** When considering multiple specific design possibilities, a comparison focused on the elements that differ among them may be most important.
- **Direct and Indirect Impact:** If the impact is primarily direct (directly from the sector), improvement may come from direct changes to production processes. If the impact is primarily indirect (coming from suppliers and suppliers' suppliers), then reduction of impact may come primarily from reduction of the use of commodities from other sectors that have most environmental impact (such as electricity).
- **Dominance of Some Life Cycle Stages:** If the use phase generates most of the environmental impact, green redesign may focus on reduction of energy consumption during use. If the manufacturing phase dominates, green redesign may focus on improved choice of materials or production processes or optimization to reduce material use. If transportation dominates, weight and packaging reduction may be important.

3. EXAMPLE SCOPING APPLICATIONS

In this section we examine two example applications of using EIO-LCA to identify major sources of greenhouse gas (GHG) emissions in the product's life cycle to support redesign and innovation efforts.

Example #1 - Coffee Maker

In considering redesign of a coffeemaker, we use the EIO-LCA model to assess GHG emissions and determine which aspect of the product dominates life cycle GHG emissions and whether they are significant compared to costs. We apply the 2002 EIO-LCA purchaser price model, which uses retail prices and accounts for transportation and retail activities associated with delivering the product to the user.

Product Purchase

We represent the production and distribution of the coffeemaker as economic activity in sector *#335210 Small Electrical Appliance Manufacturing*. Figure 1 shows a breakdown of items produced in this sector. Because the sector aggregates many types of small electrical appliances, we cannot expect estimates to be precise. The segment is dominated by vacuum cleaners, electric fans, and general electromechanical appliances. We might expect the coffeemaker to have a higher composition of plastics and fewer metals than the average product in this sector. If higher precision is required, we could break the product down into its constituent parts and examine sectors representative of those parts. We will proceed with sector 335210, recognizing that there exists uncertainty in production estimates due to sector aggregation.

Product Use

Use of the coffeemaker involves primarily consumption of coffee, filters, water, and electricity. We select sectors for each of these items, each of which has a sector breakdown that is reasonably representative of the item consumed, as shown in Figure 2.

End of Life

We ignore product disposal for this assessment, since we do not expect it to be a significant source of greenhouse gas emissions.

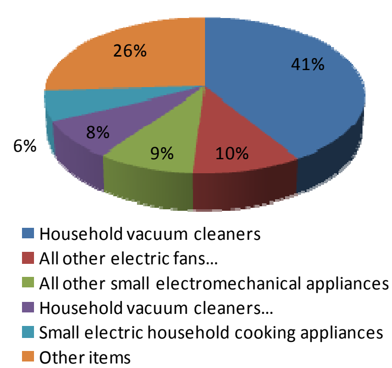
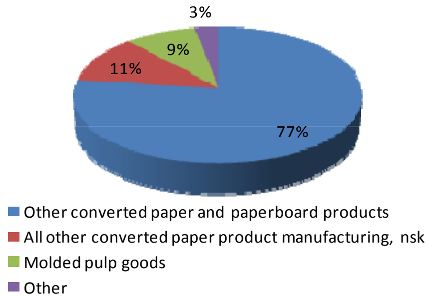
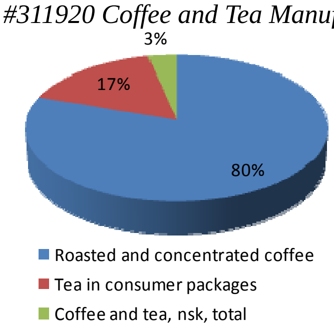


Figure 1: Breakdown of Sector #335210

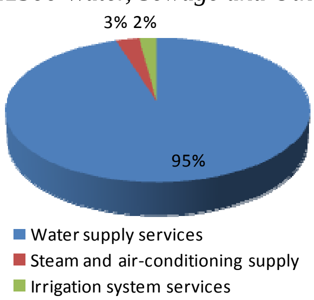
Filters: *#322299 All Other Converted Paper Product Mfg*



Coffee: *#311920 Coffee and Tea Manufacturing*



Water: *#221300 Water, Sewage and Other Systems*



Electricity: *#221100 Electric Power Generation, Transmission and Distribution*

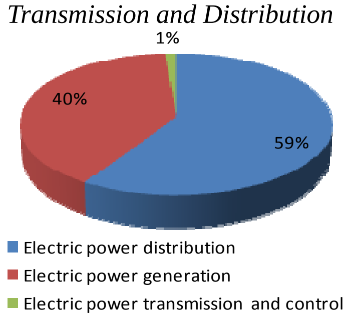


Figure 2: Breakdown of Sectors Associated with the Use Phase

Product Assessment

EIO-LCA estimates full supply chain GHG emissions per unit of economic output from each sector (typically per million dollars of output). We use these values to estimate GHG emissions per coffeemaker lifetime. To do so, we make the following assumptions:

- **Production:** The coffeemaker purchase price is $40
- **Use:** The coffeemaker is used once a day for ten years (4 cups/day) and lasts ten years
  - **Electricity:** Coffee is kept warm for ½ hour each use at 200W, using 370 kWh over the lifetime. At $0.11 per kWh, this is ~$40 of electricity over the lifetime.
  - **Filters:** One filter is consumed with each use, resulting in 3700 filters over the life. At $2 per 100 filters, this is ~$70 of filters.
  - **Coffee:** Coffee beans are used at ½ oz. per cup, resulting in ~1800 oz. coffee over the life. At $10 for 34 oz. of coffee, this is ~$530 of coffee over the life.
  - **Water:** Five cups of water is used to make four cups of coffee, resulting in 1100 gallons of water over the life. At $1.50 per 1000 gallons, this is ~$1.70 worth of water over the life.
- **End of Life:** Product disposal is ignored in this analysis

Putting data from each of these sectors together in Table 3 and Figure 3, we find that the use phase dominates the production phase. Dominant sources of GHG emissions are associated with coffee bean manufacturing and electricity production. Although there is uncertainty in assumptions about prices and use as well as the aggregate nature of the sectors, this quick assessment produces evidence to support pursuing redesign efforts that reduce electricity consumption or reduce coffee bean consumption. For example, to reduce electricity consumption during use, insulation could be increased, or a

Table 1: Top Five Sectors Contributing GHG Emissions for Power Generation and Supply Output

	Sector	$MTCO_2E$ per $1M Output
221100	Power generation and supply	8821
212100	Coal mining	230
211000	Oil and gas extraction	129
486000	Pipeline transportation	67
482000	Rail transportation	26
	Total for all sectors	9370

Table 2: Top Five Sectors Generating GHG Emissions from Coffee and tea Manufacturing

	Sector	$MTCO_2E$ per $1M Output
221100	Power generation and supply	200
1113A0	Fruit farming	68
484000	Truck transportation	40
311920	Coffee and tea manufacturing	26
211000	Oil and gas extraction	26
	Total for all sectors	609

Table 3: Evaluation of Lifetime Green House Gas (GHG) Emissions Associated with a Coffeemaker (Green House Gas Emissions estimated in metric tons of carbon dioxide equivalent, $MTCO_2E$).

	Production	Use				End of Life
	Coffeemaker Manufacturing	Filter Manufacturing	Coffee Bean Manufacturing	Water	Electricity Production	Landfill
Picture						
Sector	#335210 Small appliance manufacturing	#322299 All Other Converted Paper Product Manufacturing	#311920: Coffee and tea manufacturing	#221300 Water, sewage and other systems	#221100: Electric power generation, transmission and distribution	
MTCO2E per $1M	463	809	609	1780	9370	
Unit	coffeemaker	100 filters	34 oz. bag	1000 gallons	kWh	
Units per lifetime	1	37	53	1.1	370	
Cost per unit ($\$_{2002}$)	$40.00	$2.00	$10.00	$1.50	$0.11	
Lifetime cost ($\$_{2002}$)	$40.00	$74.00	$530.00	$1.65	$40.70	
Implied $mtCO_2e$	**0.02**	**0.06**	**0.32**	**0.00**	**0.38**	
CO_2 tax @ $30/mt	**$0.56**	**$1.80**	**$9.68**	**$0.09**	**$11.44**	
Assumptions	10 year life	1 filter/day	1/2 oz. beans per cup coffee, 4 cups/day	5 cups per day	200 Watts used 0.5 hours/day	

storage carafe could replace the pot, reducing electricity to keep the coffee warm. To reduce coffee bean consumption, a built-in measuring device could be incorporated that will help the user avoid using more than the necessary amount of coffee. Even if such design changes resulted in increased material use during production, we might expect that they would reduce overall GHG emissions if they result in significant reductions in electricity or coffee consumption.

Examination of the top two GHG producing factors shows that the bulk of emissions from power generation and supply output are primary emissions (Table 1). In contrast, the largest source of emissions associated with coffee and tea manufacturing are released during upstream production of electricity used in the production of coffee (Table 2).

Additionally, the fact that users may spend more on filters and coffee over the lifetime than they do on the coffeemaker itself motivates the use of a reusable filter, and could inspire design concepts that use brand-specific coffee or filters, such as the Keurig system.

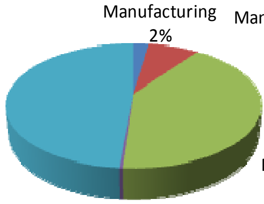


Figure 3: Breakdown of GHG Emissions in Coffeemaker LCA

Example #2 - Vehicle Fuel Tank

Acceptable light vehicle fuel tanks can be made from metal (e.g. aluminum or steel) or plastic high-density polyethylene (HDPE). This material design decision has a number of considerations, including original manufacturing cost, geometric vehicle design, safety, vehicle fuel efficiency (with operating cost, regulatory fuel efficiency standards and air emission implications), longevity and end-of-life recycling opportunities.

A comparison of steel and plastic fuel tank life cycle assessments could be done at various levels of detail. At the simplest level, attention might be restricted to simply the manufacturing impacts of the most important inputs, namely production of carbon steel sheet or plastic and resin production. A more detailed analysis would include various other inputs to the manufacturing process (e.g. transport, galvanizing and steel support straps for the plastic tank), use phase effects (e.g. changes in gasoline use), and disposal (e.g. electricity for shredding and credits for recycled steel) (Hendrickson 2005). A detailed model of this type might have purchases from roughly twenty sectors for the different fuel tanks. Each of these items has a different sector available in the EIO-LCA model.

To use the EIO-LCA model, several parameter estimates are required for this example:

- The producer prices of the various manufactured components of the fuel tanks are needed, such as the price of carbon steel sheet in the tank. These prices must be converted to the prices in the input-output model year by use of a price deflator such as the GDP deflator (NASA 2011).

Table 4. Steel Fuel Tank Inputs for Different Life Cycle Stages (Source: Table 7-1, Hendrickson 2006)

Input	EIO Sector	Input Value ($\$_{1997}$)
Tank Manufacturing		
Carbon steel sheet	Blast Furnaces and Steel Mill products	$27.18
HDPE shield material	Plastics and Resins (HDPE Shield)	$2.46
Stamping, trimming dies	Dies, Tools and Machine Accessories	$3.75
Transportation of finished tanks	Motor Freight Transportation	$1.32
Electricity	Electric Utilities	$1.06
Transportation of raw materials	Railroad Transportation	$0.31
Galvanizing and coating	Plating and Polishing Services	$0.32
Natural gas for boilers	Gas Distribution	$0.22
Packing materials	Paper and Paper Board Containers	$0.21
Paints	Paints and Allied Products	$0.16
Bearings and other repairs	Ball and Roller Bearings	$0.14
Detergents for washing tanks	Soaps and Detergents	$0.02
Lubricants and coolants	Lubricants and Greases	$0.02
Use Phase		
Gasoline	Petroleum Refining	$16.63
Disposal: Auto Shredding		
Electricity	Electric utility services	$0.07
Transportation of hulks & scrap	Motor Transportation	$0.71
Shredder tools and repairs	Dies, Tools and Machine Accessories	$0.13
Disposal: Steel Recycling		
Limestone, Lime, Florspar	Lime	$0.10
Refractories	Non Clay Refractories	$0.08
Electrodes	Carbon black	$0.27
Ferroalloys	Electro-metallurgical products	$0.08
Electricity	Electric Utilities	$0.61
Natural gas	Gas distribution	$0.07
Maintenance of EAF supplies.	Process furnaces and ovens	$0.17
Insurance	Insurance carriers	$0.07
Recovered Steel (Credit)	Blast Furnaces and Steel Mill products	-$5.08

- The fuel tank weights, the fuel savings with changes in vehicle weight and an assumption about the vehicle lifetime driving distance are needed to estimate gasoline savings.
- An assumption about the end-of-life fuel tank disposition is needed along with the relative costs and recycle credits.

Table 4 shows the different inputs estimated for the steel tank, including the extra lifetime gasoline consumption associated with the heavier steel tank. Table 5 shows inputs for the plastic tank. The inputs are based upon alternative designs for the tanks available in the literature (Keoleian 1997, Joshi 1998).

Figure 4 summarizes estimated environmental impacts using the detailed approach described above using roughly twenty sectors for each tank. The figure shows resource use and emissions as an increase in environmental impact for steel tanks relative to plastic tanks for the Chevrolet GMT600 truck line. In this case, steel tanks had higher emissions and resource inputs for all the six impact dimensions considered.

The final decision regarding fuel tank material would likely be made with consideration for multiple objectives. Manufacturing cost, crash resistance and vehicle geometric design would certainly be considered. However, the fuel economy savings and lower environmental impacts would certainly weigh in favor of a plastic fuel tank.

Table 5: Plastic Fuel Tank: Inputs for Life Cycle Stages (Source: Hendrickson 2006, Table 7.3)

Input	EIO Sector	Input Value ($$_{1997}$)
Plastic Tank Manufacture		
HDPE, PVC, EVOH	Plastics and Resins	$9.62
Steel straps and Shield	Automotive Stampings	$4.00
Electricity	Electric Utility services	$1.71
Glycol and other supplies	Industrial Org.& Inorg..Chemicals	$1.31
Natural Gas	Gas Distribution	$0.22
Packing Materials	Paper board and containers	$0.87
Molder spare parts	Special Industry Machinery parts	$0.31
Carbon Black	Carbon Black	$0.14
Adhesive layer material	Adhesives and sealants	$0.21
Inputs To Use Phase		
Gasoline	Petroleum Refining	$10.67
Inputs To Auto Shredding		
Electricity	Electric utility services	$0.05
Transportation of hulks & scrap	Motor Transportation	$0.49
Shredder tools and repairs	Dies, Tools and Machine Accessories	$0.09
Inputs to Steel Making		
Limestone, Lime, Florspar	Lime	$0.02
Refractories	Non Clay Refractories	$0.01
Electrodes	Carbon Black	$0.01
Ferroalloys	Electro-metallurgical products	$0.00
Electricity	Electric Utilities	$0.10
Natural gas	Gas distribution	$0.01
Maintenance of EAF supplies.	Industrial Process furnaces and ovens	$0.03
Insurance	Insurance carriers	$0.01
Steel Recovered (Credit)	Blast Furnaces and Steel Mill products	- $0.81

DISCUSSION

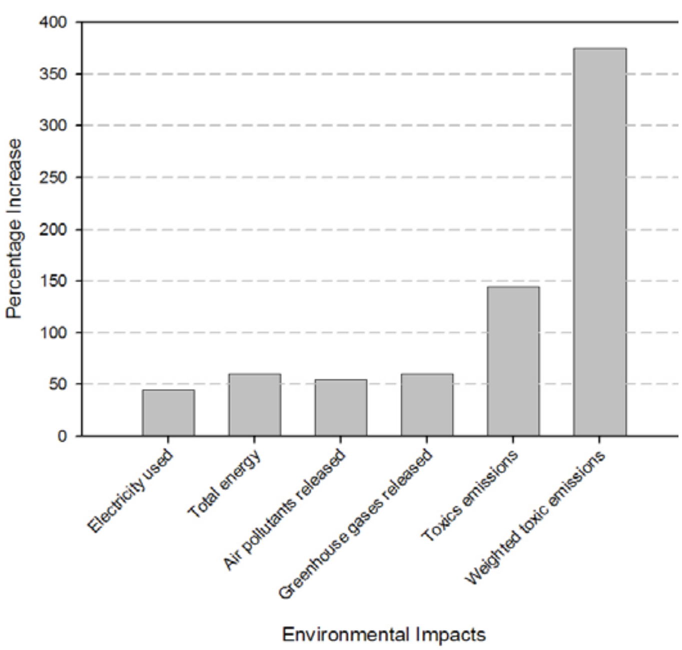


Figure 4: Steel Tank Impact Relative to Plastic Tanks (Source: Figure 7.2, Hendrickson 2005)

The economic input-output life cycle assessment tool offers a quick approach to estimating full supply chain emissions associated with the life cycle of a product. Because the model is fast to operate and easy to use, it has potential for use in the design process as a scoping exercise to guide focus of redesign efforts toward aspects of the product that are responsible for the largest share of emissions. The model is based on aggregate data of economic activity and emissions from each sector of the U.S. economy. As such, it is important to assess the degree to which the sector or sectors used to represent the product is in fact representative. In many cases sector-level information may be sufficient to determine which aspect of the product dominates its life cycle emissions. If more precision is required, a hybrid approach can be used, breaking down the product into components, collecting life cycle data where available, and using EIO-LCA to estimate full life cycle implications for aspects of the product that fall outside the boundary of what can be measured.

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