Sustainable engineering

Concepts, Design, and Case Studies

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SUSTAINABLE ENGINEERING

process steps including corn growing, transporting the corn to a refiner, refining cornstarch or corn stover into a fuel, transporting the fuel to the point of sale, and combusting the fuel. As shown in Table 2-3, life-cycle inventory data can be assembled for each of these steps.

The steps are linked by accounting for mass flows. For example, assume that 500 kg of corn and 500 kg of corn stover were grown. The initial inputs and emissions would be equal to 500 times the amounts listed in Table 2-3. If the harvested material now had to be transported to a refiner 100 km from the field where the corn plant was grown, 1 metric ton of material would need to be transported 100 km for a total transportation burden of 100 ton-km (tkm). If the fuel requirement for transporting 1 tkm of freight by truck is 0.027 L of diesel fuel (NREL, 2011), then the 2.7 L of diesel would be added to the diesel requirements of the biofuel produced from 500 kg of corn and 500 kg of stover. Similar additions would be made to all of the inputs and emissions. Then, the next process step would be added to the analysis, and this process would continue until the entire life cycle was modeled.

Tools exist in the form of data on individual process steps, and in the form of software packages that facilitate the linking of individual processes. An example of the former category is the U.S. Life Cycle Inventory (LCI) Database, maintained by the National Renewable Energy Laboratory (NREL, 2011). An example of the latter category, which is in the public domain (there are multiple software packages that can be licensed), is the GREET model. GREET, the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation model, is maintained by Argonne National Laboratory (GREET, 2011).

There are several major challenges associated with performing process life-cycle assessments. One challenge is availability of data. A review of the U.S. LCI database (NREL, 2011) reveals that while data are available for many commodity materials, there are many data gaps. A second issue is that of system boundaries. For example, the data for corn growing includes the fuel used for the tractor that plowed the fields. But what about the steel used to make the tractor? What about the materials used to construct the steel mill that made the steel that went into the tractor that plowed the fields? Where do we draw the boundary? The answers are not simple, but recently another form of life-cycle assessment that does not have these challenges has emerged: input-output LCA.

2.4.2 Input-Output LCA

An input-output LCA relies on tools that have become widely used by economists. These economic input-output tools segment national and regional economies into sectors and follow the flows of money. Consider a simple example. Imagine that a consumer purchases an automobile for $20,000. The automaker might spend $10,000 purchasing parts from first-tier suppliers. Those first-tier suppliers then might spend $1000 on steel. The steelmaker in turn might purchase coal. The transactions would continue, with the initial purchase leading to more than $50,000 eventually changing hands. Economists have built models that define these financial linkages between sectors of the economy. Typically, an economy is broken into hundreds of sectors and the financial flows between each sector and all of the other sectors are tracked, creating an economic input-output model (EIO). The EIO can be used as a life-cycle assessment tool by recognizing that for each sector, parameters such as energy use per dollar of sales can be tracked. If dollar flows between sectors are known, and if energy use per dollar is known for each sector, energy use across the economy can be tracked. This approach to modeling economy-wide flows of energy, materials, and emissions is known as an EIO-LCA. EIO-LCA models are relatively recent developments, but online tools are available (e.g., see Problem 8 at the end of the chapter).

The advantage of EIO-LCA approaches is that they track all flows up to the point of purchase. Thus, they avoid problems of system boundaries. Only limited types of flows are tracked (e.g., energy, greenhouse gases, certain toxic compounds), so this method also suffers from data gaps. It also has the disadvantage of representing products at a relatively coarse level. So, for example, all automobiles, including electric vehicles, small sedans, and large luxury cars, are averaged in the same economic sector.

2.4.3 Hybrid Approaches

Process-based and EIO-LCAs have complementary strengths and are beginning to be used in sophisticated ways. It is beyond the scope of this chapter to describe these emerging, advanced tools, but the problems at the end of this chapter will provide an introduction to the types of analyses that can be done using various analysis tools.

2.5 SUMMARY

Complex environmental and sustainability issues are best managed through structured analysis frameworks. This chapter has provided summaries of both traditional (risk-based) and emerging (life-cycle-based) frameworks. The basic principles, methodologies, and applications in environmental regulation have been summarized for both methods.

PROBLEMS

1. **Voluntary risk** Each year, approximately 45,000 persons lose their lives in automobile accidents in the United States (population 281 million according to the 2000 census). How many fatalities would be expected over a three-day weekend in the Minneapolis–St. Paul, Minnesota, metropolitan area (population 2 million)?
2. **Involuntary risk** Lurmann et al. (1999) have estimated the costs associated with ozone and fine particulate matter concentrations above the NAAQS in Houston. They estimated that the economic impacts of early mortality and morbidity associated with elevated fine particulate matter concentrations (above the NAAQS) are

approximately \$3 billion/year. Hall et al. (1992) performed a similar assessment for Los Angeles. In the Houston study, Lurmann et al. examined the exposures and health costs associated with a variety of emission scenarios. One set of calculations demonstrated that a decrease of approximately 300 tons/day of fine particulate matter emissions resulted in a 7 million person-day decrease in exposure to particulate matter concentrations above the proposed NAAQS for fine particulate matter, 17 fewer early deaths per year, and 24 fewer cases of chronic bronchitis per year. Using estimated costs of \$300,000 per case of chronic bronchitis and \$7,000,000 per early death, estimate the social cost per ton of fine particulate matter emitted.

3. **Life cycles of cups** In evaluating the energy implications of the choice between reusable and single-use cups, the energy required to heat wash water is a key parameter. Consider a comparison of single-use polypropylene (PP) and reusable PP cups. The reusable cup has a mass roughly 14 times that of the single-use cup (45 g versus 3.2 g), which, in turn requires petroleum feedstocks.
   - **a.** Calculate the number of times the reusable cup must be used in order to recoup the energy in the petroleum required to make the reusable cup.
   - **b.** Assuming that the reusable cup is washed after each use in 0.27 L of water, and that the wash water is at 80°C (heated from 20°C), calculate the energy used in each wash if the water is heated in a gas water heater with an 80% efficiency. Calculate the number of times the reusable cup must be used in order to recoup both the energy required to make the reusable cup and the energy used to heat the wash water. Assume that 1.2 kg of petroleum are required to produce 1 kg of polypropylene and that the energy of combustion of petroleum is 44 MJ/kg.
   - **c.** Repeat Part b, assuming that an electric water heater is used (80% efficiency) and that electricity is generated from fuel at 33% efficiency.

$$C_p \text{ of water} = 4.184 \text{ J/g K}$$

4. **Durability versus efficiency improvements in newer products** In minimizing the environmental footprints of products, there is tension between product durability and rapidly replacing older products with newer products that have less environmental impact associated with their use. Consider this question: When is it most energy-efficient to replace my vehicle?
   - **a.** The production of a 1995 vehicle consumed 125,000 MJ of energy, and the energy intensity of the materials used in manufacturing automobiles (energy required per kilogram of material) decreases by 1% to 2% per year. Assuming that the energy intensity of automobile manufacturing decreased by 1.5% per year between 1990 and 2010, calculate the energy required to produce a new automobile during the model years 1990, 2000, 2005, and 2010.
   - **b.** The projected average fuel economy of light-duty automobiles is expected to increase from 27.5 to 32.5 mpg between 1990 and 2020. Assume that this increase occurs in step changes, with an average fuel economy of 27.5 mpg between 1990 and 1999, 30 mpg between 2000 and 2009, and 32.5 mpg between 2010 and 2019. Calculate the amount of energy used (assuming an energy content for gasoline of 124,000 BTU/gal, $1.3 * 10^8$ J/gal) for vehicles traveling 12,000 miles per year for the decades of the 1990s, 2000s, and 2010s.
   - **c.** Is it more efficient to replace a vehicle every 10 years or every 15 years?

5. **Options for moving energy** Approximately 1 billion tons of coal are burned annually in the United States, providing 50% of the country's electricity consumption. The coal may be either moved by train from the mine to power plants near where the power is used, or combusted near the mine mouth to generate electricity that can be transmitted over long distances to the users. As a case study of this trade-off, consider electricity use in Dallas, which is generated, in part, using coal from the Powder River Basin (PRB) in Wyoming. Power plants using PRB coal supply 6.5 billion kWh of power per year to the Dallas area, at an average conversion efficiency (energy in the generated electricity per energy in the fuel burned) of 33%. The coal mined at the PRB has a heat content of 8340 BTU/lb coal (1 kWhr = 3412 BTU).
   a. Determine the amount of coal required from the PRB to support consumers in Dallas.
   b. If the energy required to transport coal by train is 0.0025 gallons of diesel per ton mile, and the distance from the PRB to Dallas is 1000 miles, calculate the amount of energy required to transport the coal to Texas, and the total energy consumed in combustion and transport. What fraction of the total energy consumption is due to transport? Assume that diesel fuel has an energy content of 124,000 BTU/gal.
   c. Calculate the amount of coal consumed if the electricity were generated at the mine (assume a 33% power plant efficiency) and if the transmission losses for the electricity, from the mine to Dallas, were 7%.
   d. Which option (transporting coal or transporting electricity) would be more efficient?
6. **Functional unit in life-cycle assessment: personal mobility** Mobility is one of the measures of quality of life that citizens of many developed nations value highly, ranked behind only food and shelter as necessities for life. Mobility is also a key factor in sustainability because of the cumulative effects of providing mobility on the environment, on resource depletion, and on the economy.

   In the table below, data are presented on two modes of transportation, automobile and bus. Use these data to answer the questions that follow.

Annual Average Personal Transportation Data for the United States

Automobiles (cars)	27.5 mpg gasoline (2010 Corporate Average Fuel Economy [CAFE] std.) 1.6 persons per automobile
Buses	mpg diesel (est.) 30 persons per bus (est.)

Source: www1.eere.energy.gov/vehiclesandfuels/facts/2010_fotw613.html

Other data and conversion factors: 150,000 BTU/gal gasoline, 163,000 BTU/gal diesel (includes production energy and feedstock energy over the fuel life cycle):

$$4.3 + 19.4 \text{ lb } CO_2 \text{ e/gal gasoline (production + combust.)}$$
$$3.6 + 22.2 \text{ lb } CO_2 \text{ e/gal diesel (production + combust.)}$$

   a. Define an appropriate functional unit for a comparison of the bus and car transportation table for personal mobility.
   b. Calculate the gallons of fuel needed to satisfy the transportation functional unit, and then convert gallons to energy (BTU per functional unit). Also, calculate the CO_2 emissions per functional unit (pounds of CO_2 emitted per functional unit).

c. Compare bus and auto transport based on energy consumption and greenhouse gas emissions.

7. Functional unit in life-cycle assessment: transport of goods Transport of goods is another important energy-consuming and greenhouse-gas-emitting activity, and, as for personal mobility, there are choices in modes of freight transportation.

In the table below, data are presented on three modes of freight transportation: by road (heavy trucks), by rail, and by ship (oceanic freighter). Use these data to answer the questions that follow.

Annual Average Freight Transportation Data for the United States

Road (heavy truck)	1 gallon diesel transports 20 tons 5.5 miles
Rail	1 gallon diesel transports 1 ton 423 miles
Ship (oceanic freighter)	1 gallon heavy oil transports 1 ton 1500 miles

Source: Transportation Energy Data Book, U.S. Department of Energy, 2010

Other data and conversion factors: 190,000 BTU/gal heavy oil, 163,000 BTU/gal diesel

$$3.7 + 26.0 \text{ lb } CO_2 \text{ e/gal heavy oil (production + combust.)}$$
$$3.6 + 22.2 \text{ lb } CO_2 \text{ e/gal diesel (production + combust.)}$$

a. Define an appropriate functional unit for a comparison of the transportation modes shown in the table for freight transportation.

b. Calculate the gallons of fuel needed to satisfy the freight transportation functional unit, and then convert gallons to energy (BTU per functional unit). Also, calculate the CO_2 emissions per functional unit (pounds of CO_2 emitted per functional unit).

c. Rank the transportation modes from the least energy- and greenhouse-gas-intensive to the most energy- and greenhouse-gas-intensive.

8. Transport of goods: truck or air? Use the U.S. Life Cycle Inventory Database (www.nrel.gov/lci) to determine the relative amount of diesel fuel required to transport 1 ton of freight 1000 km by truck and by air.

9. Economic input-output life-cycle assessment Review the input-output model for life-cycle assessment, developed by Carnegie Mellon University. This model, available at the Web site www.eiolca.net, allows you to estimate the overall environmental impacts from expending a user-defined dollar amount in any of roughly 400 economic sectors in the United States. It provides rough guidance on the relative impacts of different types of products, materials, services, and industries, up to the point of purchase.

Use the model to answer these questions:

a. What is the most energy-intensive sector of the chemical industry (resin, rubber, artificial fibers, agricultural chemicals, and pharmaceuticals sector in the EIOLCA model; measured as total life cycle energy use per million dollars of sales in the sector)?

b. What suppliers to the automotive manufacturing sector have the greatest emissions of greenhouse gases?

c. How much energy is used to manufacture a passenger vehicle costing $20,000? How does this compare to the energy consumption from driving the vehicle? Assume that the car is driven 200,000 miles and gets 30 mpg of gasoline consumed. Assume that the gasoline has a heating value of 124,000 BTU/gal and that it takes 26,000 BTU of energy to produce the gasoline.

APPENDIX: READILY AVAILABLE HAZARD REFERENCES

Although the list is not comprehensive, listed below are references commonly used to inform hazard assessment. The list is intended as a starting point for the engineer charged with hazard assessment.

1. **MSDS.** The Material Safety Data Sheet is a document developed by chemical manufacturers. The MSDS contains safety and hazard information, physical and chemical characteristics, and precautions on safe handling and use. MSDS may include hazards to animals, especially aquatic species. The manufacturer is required to keep it up-to-date. Any employer that purchases a chemical is required by law to make the MSDS available to employees. Development of an MSDS is required under OSHA's Hazard Communication Standard.
2. ***NIOSH Pocket Guide to Chemical Hazards.*** NIOSH is the National Institute for Occupational Safety and Health; this is the organization that performs research for OSHA, the Occupational Safety and Health Administration. The *Pocket Guide* may be found online at www.cdc.gov/niosh/npg/. It includes safety information, some chemical properties, and OSHA Permissible Exposure Limit concentrations, or PELs. The lower the permissible concentration, the greater the hazard to human health.
3. **IRIS.** IRIS is a database maintained by the U.S. Environmental Protection Agency. IRIS stands for Integrated Risk Information System. It is available through www.epa.gov/ngispgm3/iris/index.html. IRIS is a database of human health effects that may result from exposure to various substances found in the environment.
4. **Hazardous Substances Data Bank (HSDB).** The data bank is available from the National Library of Medicine. The Web address is http://toxnet.nlm.nih.gov. The HSDB is a toxicology data file that focuses on the toxicology of potentially hazardous chemicals. It is enhanced with information on human exposure, industrial hygiene, emergency handling procedures, environmental fate, regulatory requirements, and related areas.
5. **Toxnet.** Toxnet is also available from the National Library of Medicine. The Web address is http://toxnet.nlm.nih.gov. Toxnet is a cluster of databases on toxicology, hazardous chemicals, and related areas. Both IRIS and the HSDB are available through Toxnet.
6. **Casarett and Doull's text *Toxicology: The Basic Science of Poisons, Fifth Edition* (1996).** This is the classic text in the field for interested readers. It is published by McGraw-Hill.
7. ***Patty's Industrial Hygiene and Toxicology.*** This set of volumes is a starting point for readers who want more information than exposure limits but who are not experts in toxicology. It is published by John Wiley & Sons.