This chapter discusses the evolution of protecting human health and the environment from regulatory approaches to sustainable development, highlighting critical opportunities for engineers to design appropriate, resilient solutions. Definitions for sustainable development and design are presented. Several emerging topics are presented—green chemistry, biomimicry, green engineering, life cycle thinking, and systems thinking—offering enhancements to engineering fundamentals leading to rigorous and sustainable design solutions.

Chapter Contents

1.1 Background: Evolution from Environmental Protection to Sustainability
1.2 The Path Forward: Operationalizing Sustainability
1.3 Engineering for Sustainability
1.4 Measuring Sustainability
1.5 Policies Driving Green Engineering and Sustainability
1.6 Designing Tomorrow

Learning Objectives

1. Describe the evolution of the protection of human health and the environment from regulatory approaches to sustainability.
2. Relate *The Limits to Growth*, “The Tragedy of the Commons,” and the definition of carrying capacity to sustainable development.
3. Define sustainability, sustainable development, and sustainable engineering in your own words and according to others.
4. Redefine engineering problems in a balanced social, economic, and environmental context.
5. Apply life cycle thinking and systems thinking to problem definition and the design and assessment of proposed solutions.
6. Differentiate between traditional indicators and sustainability indicators that measure progress toward achieving the goal of sustainability.
7. Describe several frameworks for sustainable design and understand the importance of design and innovation in advancing sustainability.
8. Discuss the role of regulations and other policy tools, such as voluntary programs, in advancing environmental and human health protection as well as sustainability.
1.1 Background: Evolution from Environmental Protection to Sustainability

In 1962, Rachel Carson (Application 1.1) published *Silent Spring*, establishing the case that there may be reason to be concerned about the impacts of pesticides and environmental pollution on natural systems and human health. Though as early as 1948, there was an industrial air pollution smog release in the milltown of Donora (Pennsylvania) that killed 20 and injured thousands, it was later, in the late 1960s and early 1970s, that numerous clear and startling visual realities of human impacts on the environment took place. This included smog episodes in Los Angeles that obscured visibility, the Cuyahoga River (Ohio) catching on fire in 1969, and the toxic waste and subsequent health effects in neighborhoods such as Love Canal in Niagara Falls, New York.

Through a shared societal value and a growing environmental social movement, the Environmental Protection Agency (EPA) was created in 1972. This consolidated in one agency a variety of federal research, monitoring, standard-setting, and enforcement activities with the mission of “protecting human health and the environment.” During this same time, Congress passed many of the fundamental and critical environmental regulations, such as the National Environmental Protection Act (NEPA), the Clean Air Act, the Water Pollution Control Act, Wilderness Protection Act, and the Endangered Species Act.

The Environmental Protection Agency (EPA) is an agency of the U.S. federal government that was created for the purpose of protecting human health and the environment by writing and enforcing regulations based on laws passed by Congress (Application 1.2). Its

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**Application/1.1** Rachel Carson and the Modern Environmental Movement

Rachel Carson is considered one of the leaders of the modern environmental movement. She was born 15 miles northeast of Pittsburgh in the year 1907. Educated at the undergraduate and graduate levels in science and zoology, she first worked for the government agency that eventually became the U.S. Fish and Wildlife Service. As a scientist, she excelled at communicating complex scientific concepts to the public through clear and accurate writing. She wrote several books, including *The Sea Around Us* (first published in 1951) and *Silent Spring* (first published in 1962).

*Silent Spring* was a commercial success soon after its publication. It visually captured the fact that songbirds were facing reproductive failure and early death because of manufacturing and prolific use of chemicals such as DDT that had bioaccumulated in their small bodies. Some historians believe that *Silent Spring* was the initial catalyst that led to the creation of the modern environmental movement in the United States along with the U.S. Environmental Protection Agency (EPA).
The EPA has many tools to protect human health and the environment, including partnerships, educational programs, and grants. However, the most significant tool is writing regulations, which are mandatory requirements that can be relevant to individuals, businesses, state or local governments, nonprofit organizations, or others.

The regulatory process begins with Congress passing a law and then authorizing the EPA to help put that law into effect by creating and enforcing regulations. Of course, there are many checks and balances along the path from law to regulation, including public disclosure of intent to write or modify a regulation, and a public comment period where those potentially affected by the regulation have an opportunity to offer input to the process.

Draft and final federal regulations are published in the Code of Federal Regulations (CFR). The number 40 that is associated with environmental regulations (i.e., 40CFR) indicates the section of the CFR related to the environment.

SOURCE: http://www.epa.gov/lawsregs/basics.html

administrator, who is appointed by the president and approved by Congress, leads the agency.

The EPA has its headquarters in Washington, D.C., regional offices for each of the agency’s 10 regions (Figure 1.1) and 27 research laboratories. EPA is organized into a number of central program offices as well as regional offices and laboratories, each with its own

Figure / 1.1 The EPA’s Ten Regions Each region has its own regional administrator and other critical functions for carrying out the mission of protecting human health and the environment. EPA headquarters are located in Washington, D.C.

[Adapted from EPA]
The agency conducts environmental assessment, research, and education. It has the responsibility of maintaining and enforcing national standards under a variety of environmental laws, in consultation with state, tribal, and local governments. It delegates some permitting, monitoring, and enforcement responsibility to U.S. states and Native American tribes. EPA enforcement powers include fines, sanctions, and other measures. The agency also works with industries and all levels of government in a wide variety of voluntary pollution prevention programs and energy conservation efforts.

The mission of EPA is to protect human health and the environment. EPA’s purpose is to ensure that:

- all Americans are protected from significant risks to human health and the environment where they live, learn, and work;
- national efforts to reduce environmental risk are based on the best available scientific information;
- federal laws protecting human health and the environment are enforced fairly and effectively;
- environmental protection is an integral consideration in U.S. policies concerning natural resources, human health, economic growth, energy, transportation, agriculture, industry, and international trade, and these factors are similarly considered in establishing environmental policy;
- all parts of society—communities, individuals, businesses, and state, local, and tribal governments—have access to accurate information sufficient to effectively participate in managing human health and environmental risks;
- environmental protection contributes to making our communities and ecosystems diverse, sustainable, and economically productive;
- the United States plays a leadership role in working with other nations to protect the global environment.

EPA works closely with the states to implement federal environmental programs. States authorized to manage federal programs must have enforcement authorities that are at least as stringent as federal law. EPA works with officials in state environmental, health, and agricultural agencies on strategic planning, priority-setting, and measurement of results.

While we have made tremendous strides in addressing the most egregious environmental insults and maintained a growing economy, the environmental challenges of today are more complex and subtle than encountered at the start of the modern environmental movement. For example, there are clear connections between emissions to air, land, and water even if the regulations were not written and the EPA was not organized with these considerations.

Furthermore, air and water emissions come from many distributed sources (referred to as nonpoint source emissions), so it is much more difficult to identify a specific source that can be regulated and...
monitored. We also have a much higher level of understanding of the linkages among society, the economy, and the environment. These are recognized as the three pillars of sustainability and require that we consider them simultaneously, looking for synergies to achieve mutual benefits. That is, we must create and maintain a prosperous society with high quality of life without the negative impacts that have historically harmed our environment and communities in the name of development. And all of this must be performed while maintaining a sufficient stock of natural resources for current and future generations to maintain an increasing population with an improving quality of life.

**Application 1.3 Tragedy of the Commons**

The Tragedy of the Commons describes the relationship where individuals or organizations consume shared resources (e.g., air, freshwater; fish from the ocean) and then return their wastes back into the shared resource (e.g., air, land). In this way, the individual or organization receives all of the benefit of the shared resource but distributes the cost across anyone who also uses that resource. The tragedy arises when each individual or organization fails to recognize that every individual and organization is acting in the same way. It is this logic that has led to the current situation in ocean fisheries, the Amazon rain forest, and global climate change. In each case, the consumptive behavior of a few has led to a significant impact on the many and the destruction of the integrity of the shared resource.

**Application 1.4 The Limits to Growth and Carrying Capacity**

The Limits to Growth, published in 1972, warned of the limitations of the world’s resources and pointed out there might not be enough resources remaining for the developing world to industrialize. The authors, using mathematical models, argued that “the basic behavior mode of the world system is exponential growth of population and capital, followed by collapse” in a phenomenon known as “carrying capacity.” (see Figure 1.2)

Carrying capacity (discussed more in Chapter 5) is a way to think of resource limitations. It refers to the upper limit to population or community size (e.g., biomass) imposed through environmental resistance. In nature, this resistance is related to the availability of renewable resources, such as food, and nonrenewable resources, such as space, as they affect biomass through reproduction, growth, and survival. One solution is to use technological advances to increase the amount of prosperity per unit of resources. Of course, there is a risk that maintaining growth in a limited system by advances in technology can lead to overuse of finite resources—efficiency alone is not an effective indicator of sustainability.

Figure 1.3 provides a timeline of the progression from the start of the domestic environmental movement in the 1960s through the progression to recent major international sustainability activities. Based on the events on the timeline, there is a clear progression from initial regulatory responses to egregious environmental assaults to a more proactive, systematic international dialogue about a broad sustainability agenda.
Sperm Whales Killed (thousands)
And now the sperm whale is being hunted without limit on numbers—the ultimate folly.

Fin Whales Killed (thousands)
They switched to killing fin whales.

Sei Whales Killed (thousands)
As fin stocks collapsed, they turned to sei whales.

Worldwide Total of Whales Killed (thousands)
Since 1945, more and more whales have been killed to produce...

Worldwide Whale Oil Production (millions of barrels)
Less and less oil.

Blue Whales Killed (thousands)
First, the industry killed off the biggest whales—the blues. Then the 1940s, as stocks gave out...

Average Gross Tonnage of Catcher Boats (hundreds of tons)
Catcher boats have become bigger...

Average Horsepower of Catcher Boats (thousands)
And more powerful.

Average Production per Catcher Boat per Day's Work (barrels of whale oil)
But their efficiency has plummeted.

Figure / 1.2 Limits to Growth and Technology of the Whaling Industry
Maintaining growth in a limited system by advances in technology will eventually result in extinction for both whales and the whaling industry. As wild pods of whales are destroyed, finding the survivors has become more difficult and has required more effort. As larger whales are killed off, smaller species are exploited to keep the industry alive. Without species limits, large whales are always taken wherever and whenever encountered. Thus, small whales subsidize the extermination of large ones.


Chapter 1 Sustainable Design, Engineering, and Innovation
The Kyoto Protocol strengthens the Clean Air Act by mandating that industrial countries cut their carbon dioxide emissions by 5 to 7 percent from 1990 levels by 2008-2012. But the protocols controversial rules have been interpreted by some as too vague. This has caused repeated debates over the role of developing countries, clouding future international environmental agreements.

<table>
<thead>
<tr>
<th>Year</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>1962</td>
<td>Carson publishes <em>Silent Spring</em>, calling attention to the harms of toxic chemicals to people and the environment.</td>
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<tr>
<td>1963</td>
<td>10,000 people are killed in a single day in Bhopal, India, due to the release of methyl isocyanate gas into the air and leaching into rivers.</td>
</tr>
<tr>
<td>1964</td>
<td>Millions of people gather in the United States for Earth Day, marking the first nationwide environmental event.</td>
</tr>
<tr>
<td>1969</td>
<td>The Cuyahoga River in Ohio catches on fire, sparking the creation of the U.S. Environmental Protection Agency (EPA).</td>
</tr>
<tr>
<td>1970</td>
<td>The Endangered Species Act is passed, protecting officially recognized species from extinction.</td>
</tr>
<tr>
<td>1972</td>
<td>The Clean Water Act is passed, setting standards for the discharge of pollutants into waterways under municipal wastewater treatment plants.</td>
</tr>
<tr>
<td>1974</td>
<td>The Clean Air Act is passed, setting standards for the discharge of pollutants into atmospheres and setting a national ambient air quality standard.</td>
</tr>
<tr>
<td>1987</td>
<td>The Montreal Protocol on Substances that Deplete the Ozone Layer is adopted to support the gradual phase-out of production of a number of ozone-depleting chemicals.</td>
</tr>
<tr>
<td>1992</td>
<td>The United Nations Conference on Environment and Development (UNCED), also known as Rio+20, adopts Agenda 21, a comprehensive action plan for sustainable development that calls for improving the quality of life on Earth.</td>
</tr>
<tr>
<td>2005</td>
<td>The Kyoto Protocol enters into force after Russia and the United States ratify it.</td>
</tr>
</tbody>
</table>

Figure 1.3 Timeline of critical events leading from a mission of environmental protection to a goal of sustainability.

[Events adopted from www.worldwatch.org]
In 1986, the UN World Commission on Environment and Development released *Our Common Future*. This book is also referred to as the *Brundtland Commission* report, because Ms. Gro Brundtland, the former prime minister of Norway, chaired the commission. The Brundtland Commission report defined **sustainable development** as “development which meets the needs of the present without compromising the ability of the future to meet its needs.”

**Sustainable development** is defined by the Brundtland Commission as “development which meets the needs of the present without compromising the ability of the future to meet its needs.”

This report helped to prompt the 1992 UN Conference on Environment and Development, known as the Earth Summit, held in Rio de Janeiro, Brazil. The conference, the first global conference to specifically address the environment, led to the nonbinding agenda for the 21st century, *Agenda 21*, which set forth goals and recommendations related to environmental, economic, and social issues. In addition, the UN Commission on Sustainable Development was created to oversee the implementation of Agenda 21.

At the 2002 World Summit on Sustainable Development in Johannesburg, South Africa, world leaders reaffirmed the principles of sustainable development adopted at the Earth Summit 10 years earlier. They also adopted the **Millennium Development Goals** (MDGs), listed in Table 1.1. The eight MDGs represent an ambitious agenda for a better world that can guide engineering innovation and practice. This is a good example of the link between policy and engineering: policy can drive engineering innovation, and new engineering advancements can encourage the development of new policies with advanced standards that redefine “best available technologies.”

### 1.2 The Path Forward: Operationalizing Sustainability

Given the many definitions of sustainability (refer back to Application 1.5) and the complexity of a systems perspective to include the linkages and feedback between the environment, economy, and society, there are ongoing efforts to move from discussions to operationally...
### Table 1.1

**Millennium Development Goals (MDGs)** MDGs are an ambitious agenda embraced by the world community for reducing poverty and improving lives of the global community. Learn more at www.un.org/millenniumgoals/.

<table>
<thead>
<tr>
<th>Millennium Development Goal</th>
<th>Background</th>
<th>Example Target(s) (of 21 total targets)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Eradicate extreme poverty and hunger.</td>
<td>More than a billion people still live on less than $1 a day.</td>
<td>(1a) Halve the proportion of people living on less than $1 a day and those who suffer from hunger.</td>
</tr>
<tr>
<td>2. Achieve universal primary education.</td>
<td>As many as 113 million children do not attend school.</td>
<td>(2a) Ensure that all boys and girls complete primary school.</td>
</tr>
<tr>
<td>3. Promote gender equality and empower women.</td>
<td>Two-thirds of illiterates are women, and the rate of employment among women is two-thirds that of men.</td>
<td>(3a) Eliminate gender disparities in primary and secondary education, preferably by 2005, and at all levels by 2015.</td>
</tr>
<tr>
<td>4. Reduce child mortality.</td>
<td>Every year, nearly 11 million young children die before their fifth birthday, mainly from preventable illnesses.</td>
<td>(4a) Reduce by two-thirds the mortality rate among children under 5 years.</td>
</tr>
<tr>
<td>5. Improve maternal health.</td>
<td>In the developing world, the risk of dying in childbirth is one in 48.</td>
<td>(5a) Reduce by three-quarters the ratio of women dying in childbirth.</td>
</tr>
<tr>
<td>6. Combat HIV/AIDS, malaria, and other diseases.</td>
<td>40 million people are living with HIV, including 5 million newly infected in 2001.</td>
<td>(6a and 6c) Halt and begin to reverse the spread of HIV/AIDS and the incidence of malaria and other major diseases.</td>
</tr>
<tr>
<td>7. Ensure environmental sustainability.</td>
<td>768 million people lack access to safe drinking water and 2.5 billion people lack improved sanitation.</td>
<td>(7a) Integrate the principles of sustainable development into country policies and programs and reverse the loss of environmental resources. (7b) Reduce by half the proportion of people without access to safe drinking water. (7c) Achieve significant improvement in the lives of at least 100 million slum dwellers.</td>
</tr>
<tr>
<td>8. Develop a global partnership for development.</td>
<td></td>
<td>(8a) Develop further an open, rule-based, predictable, nondiscriminatory trading and financial system. (8b) Address the special needs of the least-developed countries. (8c) Address the special needs of landlocked countries and small island developing states. (8d) Deal comprehensively with the debt problems of developing countries through national and international measures to make debt sustainable in the long term. (8e) In cooperation with pharmaceutical companies, provide access to affordable, essential drugs in developing countries. (8f) In cooperation with the private sector, make available the benefits of new technologies, especially information and communications.</td>
</tr>
</tbody>
</table>

**SOURCE:** www.un.org/millenniumgoals/.
applying a sustainability framework to organizational and engineering activities. There are often considered to be two broad classes of efforts to operationalize sustainability: top-down and bottom-up. That is, one strategy involves high-level decision-makers initiating activities and establishing organizational structures and incentives to push sustainability into the organization from the top. In the other strategy, people throughout the organization are motivated to pursue their functions in a more sustainable manner and drive sustainability into the organization through grassroots initiatives and self-initiated activities.

There are examples of successful changes from governmental and nongovernmental organizations as well as major corporations that have been realized from both of these approaches, but the most successful examples are when all levels of the organization are working toward sustainability outcomes. A successful example of this evolution to operationalize sustainability can be seen in the Path Forward at the Office of Research and Development at the EPA (described in Application 1.6). Once there is an intention to pursue sustainability, there is a clear need to identify an approach to problem solving that is evolved from previous approaches which had not systematically incorporated triple bottom-line considerations. There are two critical frameworks that can be utilized to support the expanded view necessary to move toward sustainability goals: life cycle thinking and systems thinking. While these two frameworks are related, there are clear differences where life cycle thinking is focused on material and energy flows and the subsequent impacts, while systems thinking can also capture the relationship of political, cultural, social, and economic considerations, and potential feedbacks between these considerations and material and energy flows.
1.2.1 LIFE CYCLE THINKING

Life cycle thinking supports recognizing and understanding how both consuming products and engaging in activities impact the environment from a holistic perspective. That is, life cycle considerations take into account the environmental performance of a product, process, or system from acquisition of raw materials to refining those materials, manufacturing, use, and end-of-life management. Figure 1.5a depicts the common life cycle stages for a consumer product. In the case of engineering infrastructure, Figure 1.5b depicts the life cycle stages of: (1) site development, (2) materials and product delivery, (3) infrastructure manufacture, (4) infrastructure use, and (5) end-of-life issues associated with infrastructure refurbishment, recycling, and disposal. In some cases, the transportation impacts of moving between these life cycle stages are also considered.

There is a need to consider the entire life cycle, because different environmental impacts can occur during different stages. For example, some materials may have an adverse environmental consequence when extracted or processed, but may be relatively benign in use and easy to recycle. Aluminum is such a material. On one hand, smelting of aluminum ore is very energy intensive. This is one reason aluminum is a favored recycled metal. However, an automobile will create the bulk of its environmental impact during the use life stage, not only because of combustion of fossil fuels, but also because of runoff from roads and the use of many fluids during operation. And for buildings, though a vast amount of water, aggregate, chemicals, and energy goes into the production of construction materials, transport of these items to the job site, and construction of a building, the vast amount of water and energy occurs after occupancy, during the operation life stage of the building.
Figures 1.5a and 1.5b also show, as feedback loops, the potential for recycling, remanufacturing, and reuse. While there are often benefits associated with these various end-of-life handling strategies, they can also carry environmental impacts and should be included when making design or improvement designs and in life cycle considerations.

Further, and potentially most importantly, life cycle thinking will minimize the possibility of shifting impacts from one life cycle stage to another by considering the entire system. For example, efforts to reduce the energy demands of lighting led to the installation of millions of compact fluorescent light bulbs (CFLs) (Application 1.7). However,
CFLs contain a small amount of mercury. By focusing solely on reducing energy demand and carbon emissions, while not considering the toxicity associated with manufacturing and disposing of CFLs, there is the potential to have a greater environmental and human health impact associated with the mercury, a heavy metal with known neurotoxic effects. By using life cycle thinking, one can begin to understand and evaluate these potential trade-offs across many environmental and human health endpoints such as energy use, carbon emissions, water use, eutrophication, solid waste production, and toxicity by tracking all of the material and energy inputs associated with not just using energy for lighting but producing and disposing of light bulbs. These trade-offs can be quantified through a tool known as life cycle assessment (LCA).

Life cycle thinking supports the goal of improving the overall environmental performance of an engineering design and not simply improving a single stage or endpoint while shifting burdens elsewhere in the life cycle. To effectively capture these impacts across the entire electricity generation is taken for lighting, there is the potential for tremendous savings associated with new alternative lighting technologies.

CFLs contain approximately 4.0 mg of mercury per bulb, raising environmental and human health concerns. Further, initially there were performance considerations associated with CFLs that have led to resistance in the market, including lighting quality and warm-up time. While mercury is not used in the manufacture of LED bulbs, there are still life cycle impacts associated with their production, use, and disposal. However, LED lamps solve many of the performance considerations associated with CFLs. To make the situation even more complex, the cost of CFLs and LEDs is higher than that of incandescent light bulbs. Generally, this extra cost is repaid in the long term, as both lighting technologies use less energy and have longer operating lives than incandescent bulbs.

From this discussion, there are clear opportunities to improve the energy consumption, and subsequent carbon emissions, associated with lighting. However, the technological advances present some trade-offs in terms of mercury use and disposal and performance for CFLs and cost for both CFLs and LEDs. These trade-offs need to be considered and quantified for informed decision making in the present and should be used to guide future design and innovation for improved lighting technologies in the future.
life cycle of the product, process, or system, one must consider the environmental impacts for the entire life cycle through an LCA.

An LCA is a sophisticated way of examining the total environmental impact through every life cycle stage. The LCA framework is depicted in Figure 1.6. LCAs can be used to identify processes, ingredients, and systems that are major contributors to environmental impacts, compare different options within a particular process with the objective of minimizing environmental impacts, and compare two different products or processes that provide the same service.

As shown in Figure 1.6, the first step in performing an LCA is to define the goal and scope. This can be accomplished by answering the following questions:

- What is the purpose of the LCA? Why is the assessment being conducted?
- How will the results be used, and by whom?
- What materials, processes, or products are to be considered?
- Do specific issues need to be addressed?
- How broadly will alternative options be defined?
- What issues or concerns will the study address?

Another item that needs to be addressed at this stage is to define the function and functional unit. The functional unit serves as the basis of the LCA, the system boundaries, and the data requirements and assumptions. For example, if you were interested in determining the energy use and associated carbon emissions from reclaiming or desalinating water (over the complete life cycle), the function would be to reclaim treated wastewater or desalinate ocean water. The associated functional unit might therefore be m$^3$ of reclaimed wastewater or m$^3$ of desalinated water.

Once the goal, scope, and functional unit have been defined, the next step of an LCA is to develop a flow diagram for the processes being evaluated and conduct an inventory analysis. This involves describing all of the inputs and outputs (including material, energy, and water) in a product’s life cycle, beginning with what the product is composed of, where those materials came from, where they go, and the inputs and outputs related to those component materials during their lifetime. It is also necessary to include the inputs and outputs during the product’s use, such as whether the product uses electricity or batteries. If the analysis strictly focuses on materials and does not consider energy or other inputs/outputs, it is referred to as a subset of LCA and materials flow analysis.

A materials flow analysis (MFA) measures the material flows into a system, the stocks and flows within it, and the outputs from the system. In this case, measurements are based on mass (or volume) loadings instead of concentrations. Urban materials flow analysis (sometimes referred to as an urban metabolism study) is a method to quantify the flow of materials that enter an urban area (e.g., water, food, and fuel) and the flow of materials that exit an urban area (e.g., manufactured goods, water and air pollutants including greenhouse gases, and solid wastes) (Application 1.8).
example 1.1 Determining Function and Functional Unit in Terms of LCA

Example 1
If you are asked to conduct an LCA on two different laundry detergents, what could you use as the functional unit for the analysis?

Solution 1
The basis of the LCA could be the weight or volume of each laundry detergent necessary to run 1,000 washing machine cycles. (This says nothing about the performance of the laundry detergents—how clean the clothes are after washing—as that is assumed to be identical for the purpose of the LCA.)

Example 2
If you are asked to conduct an LCA on paper versus plastic grocery bags, what could you use as the functional unit for the analysis?

Solution 2
The basis of the LCA could be a set volume of groceries to be carried, in which case two plastic bags might be equivalent to one paper bag. Or the functional unit could be related to the weight of groceries carried, in which case you would need to determine whether paper or plastic bags are stronger and how many of each would be needed to carry the specified weight.

Application 1.8 Urban Metabolism and a Case Study on Hong Kong

Urban metabolism studies are important, because planners and engineers can use them for recognizing problems and wasteful growth, setting priorities, and formulating policy. For example, a materials flow analysis performed over 10 years on the quantity of freshwater that enters and exits the Greater Toronto Area found that water inputs had grown 20 percent more than the outputs. Possible explanations for this could be leaking water distribution systems, combined sewer overflow events, and increased use of water for lawn care, all of which would allow inputted water to bypass output monitoring. The analysis also pointed to a need to further develop water conservation because of a fixed availability (or storage capacity) of freshwater.

Figure 1.7 shows the results of a materials flow analysis performed on the city of Hong Kong. Here, 69 percent of the building materials were used for residential purposes, 12 percent for commercial, 18 percent for industrial, and 2 percent for transport infrastructure. Also, a 3.5 percent measured increase in materials use over the 20-year study period indicated that Hong Kong was still developing into a larger urban system.

During the study period, the city’s economy shifted from manufacturing to a service-based center. This resulted in a 10 percent energy shift from the industrial sector to the commercial sector, yet energy consumption rose. The large increase in energy use was attributed to increases in development and residential/occupational comfort and convenience. The rate of use of consumable materials also rose during the study period, with plastics actually increasing 400 percent.

Overall air emissions in Hong Kong decreased; however, air pollutants associated with motor vehicle use and fossil fuel power production (such as NOx and CO) increased. Land disposal of solid waste rose by 245 percent, creating a dilemma for the space-limited city. Although a large portion of this waste is construction, demolition, and reclamation waste,
municipal solid waste also rose 80%, with plastics, food scraps, and paper contributing the most to municipal waste.

Though the overall rate of growth for water use declined over the study (10–2 percent) from decreases in agriculture and industrial use, the per capita freshwater consumption rose from 272 to 379 L/day. Water is one of the major waste sinks for the city, due to its large volume of untreated sewage. Biochemical oxygen demand (BOD) loadings increased by 56 percent. Nitrogen discharges also increased substantially. Sewage contamination in Hong Kong waters is now considered a major crisis for the city, having large harmful environmental, economic, and health effects.

One conclusion is that, at its current urban metabolic rate, Hong Kong is exceeding its own natural production and CO₂ fixation rates. Materials and energy consumption in the city greatly outweigh the natural assimilation capacity of the local ecosystem. High urban metabolism rates show that, relative to other cities, Hong Kong is more efficient (on a per capita basis) in land, energy, and materials use due to lower material stocks in buildings and transportation infrastructure, has less energy and materials use (domestic consumption), and has higher proportions of space dedicated to parks and open space.

![Figure 1.7 Important Materials Flows into and through the City of Hong Kong](image)

All units are in tonnes per day. Arrows are intended to give some indication of the direction of flow of materials.

The purpose of an inventory analysis—either a full life cycle or limited to materials—is to quantify what comes in and what goes out, including the energy and material associated with each stage in the life cycle. Inputs include all materials, both renewable and nonrenewable, and energy. It is important to remember that outputs include the desired products as well as by-products and wastes such as emissions to air, water, and land. It is also important to consider the quality of data for inputs and outputs to the system when conducting an inventory analysis.

The third step in an LCA (or MFA) is to conduct an impact assessment. This step involves identifying all the environmental impacts associated with the inputs and outputs detailed in the inventory analysis. In this case, the environmental impacts from across the life cycle are grouped together in broad topics. Environmental impacts can include stressors such as resource depletion, water use, energy use, global warming potential, ozone hole depletion, human toxicity, smog formation, and land use. This step often involves some assumptions about what human health and environmental impact will result from a given emission.

The final step in the impact assessment can be controversial, as it involves weighting these broad environmental impact categories to yield a single score for the overall environmental performance of the product, process, or system being analyzed. This is often a societal consideration that can vary between cultures. For example, Pacific Rim Island nations may give greater weighting to climate change given their vulnerability to sea level rise, while other countries may give greater weighting to human health impacts. This suggests that the total impact score may be distorted by weighting factors. It also means that for an identical life cycle inventory, the resulting decisions from the impact assessment may vary from country to country or organization to organization.

Ultimately, LCA (and MFA) can provide insight into opportunities for improving the environmental impact of given product, process, or system. This can include choosing between two options or identifying areas for improvement for a single option. LCA and MFA are extremely valuable in ensuring that environmental impact is being minimized across the entire life cycle and that impacts are not being shifted from one life cycle stage to another. This leads to a system that is globally optimized to reduce adverse effects of the specified product, process, or system.

### 1.2.2 SYSTEMS THINKING

Beyond tracking the physical inputs and outputs to a system, systems thinking considers component parts of a system as having added characteristics or features when functioning within a system rather than in isolation. This suggests that systems should be viewed in a holistic manner. Systems as a whole can be better understood when the linkages and interactions between components are considered in addition to understanding the individual components. An example of the benefit of using life cycle thinking and systems thinking for the issue of assessing the potential environmental impact of biofuels is presented in Application 1.9.
The nature of systems thinking makes it extremely effective for solving the most difficult types of problems. For example, sustainability challenges are quite complex, depend on interactions and interdependencies, and are currently managed or mitigated through disparate mechanisms. In this way, policies or technologies may be implemented with well-articulated goals, but can lead to unintended consequences because all of the potential system feedbacks were not considered.

One way to begin a systems analysis is through a causal loop diagram (CLD). CLDs provide a means to articulate the dynamic, interconnected nature of complex systems. These diagrams consist of arrows connecting variables (things that change over time) in a way that shows how one variable affects another. Each arrow in a CLD is labeled with an s or o. An s means that when the first variable changes, the second one changes in the same direction. (For example, increased profits lead to increased investments in research and development.) An o means that the first variable causes a change in the opposite direction of the second variable. (For example, more green engineering innovations can lead to reduced environmental and human health liabilities.)

In CLDs, the arrows come together to form loops, and each loop is labeled with an R or B (Figure 1.9). R means reinforcing—that is, the causal relationships within the loop create exponential growth or collapse. For instance, Figure 1.9 shows that the more fossil fuel–based energy consumed, the more carbon dioxide that is emitted, as the global temperatures increase, and the more energy that needs to be consumed. B means balancing—that is, the causal influences in the loop keep the variables in equilibrium. For example, in Figure 1.9, the more profits generated by a company, the more research and development investments that can be made, which will lead to increased environmental and human health impacts.

Application /1.9 Life Cycle and Systems Thinking Applied to Biofuels

A recent example where the relevance of life cycle thinking and systems thinking was made clear was the proposal to use biobased fuels to replace a portion of the U.S. transportation fuel portfolio. There has been significant emphasis placed on alleviating dependence on fossil fuel by producing fuel energy from agricultural products. One of the clearest examples of this is the emphasis in the United States on producing ethanol from corn. Whether the economics of producing ethanol from corn is considered by monetizing life cycle emissions or direct environmental impacts (including water, fertilizer, and pesticide application), corn-based ethanol may require (per unit of fuel produced) more fossil fuel and fertilizer inputs that emit large amounts of greenhouse gases, particulate matter, and nutrients than the current petroleum-based production.

This is not to suggest that producing energy from biobased resources is not an appropriate or ultimately sustainable strategy. It is rather to suggest that pursuing renewable energy in a way that only addresses the singular goal of reducing use of finite resources can lead to increased environmental and human health impacts and even greater stress on the earth’s systems without using life cycle and systems thinking frameworks. Figure 1.8 shows the environmental impact of biofuels created from different crops sources. Note how this supposed “greener” fuel can have significant and varied environmental impacts across the life cycle. These impacts are also highly dependent on the feedstock choice and production location.
### Figure / 1.8 Overview of the Diversity of Environmental Effects from Various Renewable Feedstocks for the Production of Biodiesel

Environmental impacts are reported relative to the production of petroleum-based petrol mix with lighter shading indicating less impact and darker shading indicating greater impact than the conventional system. Based on material from the Seattle Post-Intelligencer (2008).
more green engineering innovations, reducing the number of environmental and human health liabilities, which leads to greater potential profits.

CLDs can contain many different R and B loops, all connected with arrows. Drawing these diagrams can develop a deep understanding of the system dynamics. Through this process, opportunities for improvements will be highlighted. For example, the links between finite resource consumption for energy production, carbon emissions, and global temperatures may lead us to find new sources of renewable energy.

Further, it is through systems thinking that we can also begin to understand the resilience of a system. Resiliency is a very important concept for sustainable systems because it is the capacity of system to survive, adapt, and grow in the face of unforeseen changes, even catastrophic incidents (Fiksel, 2003). Resilience is a common feature of complex systems, such as companies, cities, or ecosystems. Given the uncertainty and vulnerability around sustainability challenges such as climate change, water scarcity, and energy demands, sustainable designs likely will need to incorporate resilience as a fundamental concept.

The idea of designing engineered systems for resilience would be to introduce more distributed and/or smaller systems that can continue to effectively function in uncertain situations with greater resilience. Examples include power generation and rainwater harvesting at the household or community level, and decentralized wastewater treatment. Again, it is necessary to consider the life cycle impacts of the entire system when designing a new, distributed system with more redundancy to replace a more centralized system. This is in order to understand the potential trade-offs between environmental and human health impacts for resiliency gains. This is where the lifetime of a given system becomes a crucial factor in LCA.
1.3 Engineering for Sustainability

Engineers, in particular, have a unique role to play in the Path Forward to a sustainable future. This is because they have a direct effect on the design and development of products, processes, and systems, as well as on natural systems through material selection, project siting, and the end-of-life management of chemicals, materials, and products. Engineers play a significant and vital role in nearly all aspects of our lives. They provide basic services such as water, sanitation, mobility, energy, food, health care, and shelter, in addition to advances such as real-time communications and space exploration. The implementation of all of these engineering achievements can lead to benefits as well as problems in terms of the environment, economy, and society. The adverse impacts of traditional engineering design, often implemented without a sustainability perspective, can be found all around us in the form of water use inefficiencies, depletion of finite material and energy resources, chemicals with unintentional toxicity impacts, and degradation of natural systems.

Engineers must develop and implement solutions with an understanding of the potential benefits and impacts over the lifetime of the design. In this way, the traditions of innovation, creativity, and brilliance that engineers use to find new solutions to any challenge can be applied to designing sustainable solutions—that is, solutions that not only address grand societal challenges but also are in, and of themselves, sustainable by not creating legacy adverse impacts on the environment.
environment and society. Mutual benefits resulting from this green engineering view of design include a competitive and growing economy in the global marketplace, improved quality of life for people, and enhanced protection and restoration of natural systems.

### 1.3.1 FRAMEWORKS FOR SUSTAINABLE DESIGN

To support the design of these sustainable solutions, the **Principles of Green Engineering** (Application 1.10) were developed to provide a framework for thinking in terms of sustainable design criteria that, if followed, can lead to useful advances for a wide range of engineering problems.

**Green chemistry** is a field devoted to the design of chemical products and processes that reduce or eliminate the use and generation of hazardous materials (Anastas and Warner, 1998). Green chemistry focuses on addressing hazard through molecular design and the processes used to synthesize those molecules.

The fields of green chemistry and green engineering also use the lessons and processes of nature to inspire design through biomimicry (Benyus, 2002). **Biomimicry** (from *bios*, meaning life, and *mimesis*, meaning to imitate) is a design discipline that studies nature’s best ideas and then imitates these designs and processes to solve human problems. Studying a leaf to invent a better solar cell is an example of this “innovation inspired by nature” (Benyus, 2002).

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**Application 1.10  The Principles of Green Engineering (from Anastas and Zimmerman, 2003)**

**Green engineering** is the design, discovery, and implementation of engineering solutions with an awareness of these potential benefits and impacts throughout the lifetime of the design. The goal of green engineering is to minimize adverse impacts while simultaneously maximizing benefits to the economy, society, and the environment.

**The 12 Principles of Green Engineering**

1. Designers need to strive to ensure that all material and energy inputs and outputs are as inherently nonhazardous as possible.
2. It is better to prevent waste than to treat or clean up waste after it is formed.
3. Separation and purification operations should be a component of the design framework.
4. System components should be designed to maximize mass, energy, and temporal efficiency.
5. System components should be output pulled rather than input pushed through the use of energy and materials.
6. Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.
7. Targeted durability, not immortality, should be a design goal.
8. Design for unnecessary capacity or capability should be considered a design flaw. This includes engineering “one size fits all” solutions.
9. Multi-component products should strive for material unification to promote disassembly and value retention (minimize material diversity).
10. Design of processes and systems must include integration of interconnectivity with available energy and materials flows.
11. Performance metrics include designing for performance in commercial “afterlife.”
12. Design should be based on renewable and readily available inputs throughout the life cycle.
Application /1.11  Examples of Green Chemistry

The fundamental research of green chemistry has been brought to bear on a diverse set of challenges, including energy, agriculture, pharmaceuticals and health care, biotechnology, nanotechnology, consumer products, and materials. In each case, green chemistry has been successfully demonstrated to reduce intrinsic hazard, to improve material and energy efficiency, and to ingrain a life cycle perspective.

Some examples of green chemistry that illustrate the breadth of applicability include:

- a dramatically more effective fire extinguishing agent that eliminates halon and utilizes water in combination with an advanced surfactant;
- production of large-scale pharmaceutical active ingredients without the typical generation of thousands of pounds of toxic waste per pound of product;
- elimination of arsenic from wood preservatives that are used in lumber applied to household decks and playground equipment;
- introduction of the first commodity bio-based plastic that has the performance qualities needed for a multimillion pound application, as a food packaging;
- a new solvent system that eliminates large-scale ultrapure water usage in computer chip manufacture, replacing it with liquid carbon dioxide, which allows for the production of the next generation of nano-based chips.

Application /1.12  Examples of Biomimicry

Three levels in biology can be distinguished from which innovative and sustainable technology can be modeled:

- Mimicking natural methods of manufacture of chemical compounds to create new ones
- Imitating mechanisms found in nature (e.g., velcro)
- Studying organizational principles from social behavior of organisms, such as the flocking behavior of birds or the emergent behavior of bees and ants

Pigment-Free Color: There can significant environmental impacts associated with dyes, inks, coatings, and paints. Looking to natural systems for ideas of how to create color, one quickly finds that nature uses structure rather than pigment to offer the brilliant hues seen on butterflies, peacocks, and hummingbirds. The colors seen result from light scattering off regularly spaced melanin rods and interference effects through thin layers of keratin. Qualcomm is mimicking this strategy to create screens for electronic devices.

Preservatives: One of the emerging chemical classes of concern are anti-microbials used in a range of applications from personal care products to industrial systems. Using biomimicry as a tool, one would look for organisms that inherently demonstrate this desirable trait. For example, red and green algae produce halogenated metabolites, primarily utilizing bromide, that have demonstrated antimicrobial activity. Based on this approach, Nalco developed a product, Stabrex™, a chlorine alternative to maintaining industrial cooling systems.

Clean without chemicals: There are many environmental and human health concerns associated with certain classes of detergents and soaps. So how does nature provide the service of cleanliness without potentially toxic chemicals? One example to consider how the lotus plant that prevents dirt from interfering with photosynthesis. Lotus leaves have rough hydrophobic surfaces that allow dirt to be carried away by drops of water that “ball up” and roll off the surface. A number of new products have emerged based on this “lotus-effect,” including Lotusan paint that provides a similar molecular-structure to the lotus leaf such that dirt is carried away by the rain providing “self-cleaning” building exteriors.

1.3.2 THE IMPORTANCE OF DESIGN AND INNOVATION IN ADVANCING SUSTAINABILITY

Embedded in the discussion of sustainability and engineering is the word design. Design is the engineering stage where the greatest influence can be achieved in terms of sustainable outcomes. At the design stage, engineers are able to select and evaluate the characteristics of the final outcome. This can include material, chemical, and energy inputs; effectiveness and efficiency; aesthetics and form; and intended specifications such as quality, safety, and performance.

The design state also represents the time for innovation, brainstorming, and creativity, offering an occasion to integrate sustainability goals into the specifications of the product, process, or system. Sustainability should not be viewed as a design constraint. It should be utilized as an opportunity to leapfrog existing ideas or designs and drive innovative solutions that consider systematic benefits and impacts over the lifetime of the design.

This potential is shown in Figure 1.10. This figure demonstrates that allowing an increased number of degrees of freedom to solve a challenge, address a need, or provide a service creates more design space to generate sustainable solutions.

For a given investment (time, energy, resources, capital), potential benefits can be realized. These benefits include increased market share, reduced environmental impact, minimized harm to human health, and improved quality of life. In the case in which constraints require merely optimizing the existing solution or making incremental improvements, some modest gains can be achieved. However, if the degrees of freedom within the design space can be increased, more benefits can be realized. This is because the engineer has an

Class Discussion
Are there toxic chemicals used in nature? How are they “managed”? What lessons can we mimic from how toxic chemicals are generated or used in natural systems?

Learn more about the theory of leapfrog or disruptive innovation
http://blogs.hbr.org/video/2012/03/disruptive-innovation-explain.html

Class Discussion
What is an example of leapfrog or disruptive innovation that had a positive impact toward sustainability? What are the potential trade-offs of full-scale implementation of this innovation?

Figure / 1.10 Increasing Potential Benefits with Increasing Degrees of Design Freedom for a Given Investment Note that allowing an increased number of degrees of freedom to solve a problem frees up more design space to innovate and generate sustainable solutions.
opportunity to design a new solution that may appear very different in form but provides the same service. This may pose challenges if the new design is too embedded into an existing and constrained system. Ultimately, the most benefits can be achieved when the engineer designs with the most degrees of freedom—at the highest system scale—to ensure that each component within the system is sustainable, performs with the other system components, and meets the overall intended purpose.

example 1.3 Degrees of Freedom and Sustainable Design

In 2004, the average miles per gallon for a car on the road in the United States was 22. In response to concerns about global climate change, policy makers and engineers are working toward a more innovative technical and management strategies to improve gas mileage and lower carbon dioxide emissions. What are the design opportunities for improvement scaled with increasing degrees of freedom and what are the potential benefits?

solution

Table 1.2 gives three design solutions. As the degrees of freedom in the design increase, engineers in this example have more flexibility to innovate a solution to the problem.

<table>
<thead>
<tr>
<th>Increasing degrees of freedom</th>
<th>Incremental Improvement</th>
<th>Reengineer the System</th>
<th>Redefine the System Boundary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design solution</td>
<td>Improve the efficiency of the Carnot engine; use lightweight materials (composites instead of metals)</td>
<td>Use a hybrid electric or fuel cell system for energy; change the shape of the car for improved aerodynamics; capture waste, heat, and energy for reuse</td>
<td>Meet mobility needs without individual car; implement a public transit system; design communities so commercial districts and employment are within walking and cycling distance; provide access to desired goods and services without vehicular transportation</td>
</tr>
<tr>
<td>Potential realized benefits</td>
<td>Moderate fuel savings; moderate reductions in CO₂ emissions</td>
<td>Improved fuel savings; improved reductions in CO₂ emissions; improved material and energy efficiency</td>
<td>Elimination of the environmental impacts associated with the entire automobile life cycle; maximized fuel savings and CO₂ reductions; improved infrastructure; denser development (smart growth); improved health of society from walking and less air pollution</td>
</tr>
</tbody>
</table>
The design phase also offers unique opportunities in the life cycle of an engineered product, process, or system. As shown in Figure 1.11, it is at the design phase of a typical product that 70–75 percent of the cost is set, even though these costs will not be realized until much later in the product life cycle. The environmental costs are analogous to economic ones. For example, it is also at the design phase that materials are specified. This often dictates the production process as well as operation and maintenance procedures (i.e., painting, coating, rust inhibiting, cleaning, and lubricating).

As soon as a material is specified as a design decision, the entire life cycle of that material from acquisition through processing as well as the end of life is now included as a part of the environmental impacts of the designed product, process, or system. Therefore, it is at the design phase that the engineer has the greatest ability to affect the environmental impacts associated with the final outcome.

As an example, think of all the materials and products that go into construction and furnishing a building. At this point, the engineer needs to vision the future in regard to how these materials will be maintained, what cleaning agents will be used, what the water and energy demands of the building will be, what will happen to the building after its useful life is over, and what the fate of these materials at the end of the building’s life will be. In terms of transportation systems, an engineer can think beyond the design of a new highway intended to relieve urban congestion, because data clearly shows that these new transportation corridors will become congested in just a few years after the highway is completed.

It is also important to note that it is at the design phase that the engineer has the opportunity to incorporate increased efficiency, reduced waste of water, materials, and energy, reduce costs, and most importantly, impart new performance and capabilities. While many of the other attributes listed can be achieved through “end of the pipe” control technologies, it is only by working at the design phase

**Figure 1.11 Percent Costs Incurred versus Design Timeline** The costs can be thought of as economic or environmental. During the design phase, approximately 70 percent of the cost becomes fixed for development, manufacture, and use.

EPA’s Design for Environment Program
http://www.epa.gov/oppt/dfe
that the actual product, process, or system characteristics can be changed. Choosing a material that is inherently nontoxic has tremendous benefits in terms of human health and environmental impacts as well as eliminating the need to control the circumstances in which this chemical is used and how it is handled. Adding new performance and/or capabilities often brings improved environmental characteristics as well as offering the opportunity for improved competitiveness and market share making this a better design for many reasons. Simply controlling or minimizing waste through manufacturing or even end of life cannot alter or improve the fundamental nature of the design, which adds value while offering an improved environmental profile. There is even a new recognition that wastewater should be viewed as a source of water, energy, and nutrients, and not just something to be remediated to the minimum standard as cheaply and quickly as possible. This can have a tremendous impact on the design of next generation wastewater treatment and resource recovery systems.

1.4 Measuring Sustainability

An **indicator**, in general, is something that points to an issue or condition. Its purpose is to show you how well a system is working. If there is a problem, an indicator can help you determine what direction to take to address the issue. Indicators are as varied as the types of systems they monitor. However, there are certain characteristics that effective indicators have in common (Sustainable Measures, 2007) as given in Table 1.3.

![Table 1.3](image)

<table>
<thead>
<tr>
<th>Characteristics and Intentions of Effective Indicators</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relevant</td>
</tr>
<tr>
<td>Easy to understand by all stakeholders</td>
</tr>
<tr>
<td>Reliable</td>
</tr>
<tr>
<td>Quantifiable</td>
</tr>
<tr>
<td>Based on accessible data</td>
</tr>
</tbody>
</table>

Source: From the Community Indicators Consortium [www.communityindicators.net].

An example of an indicator is the gas gauge in your car. The gas gauge shows you how much gasoline is left in your car. If the gauge shows that the tank is almost empty, you know it is time to fill up. Another example of an indicator is a midterm report card. It shows a student and instructor whether they are doing well enough to go to the next grade or whether extra help is needed. Both of these indicators provide information to help prevent or solve problems, hopefully before they become too severe. Another example of a common one-dimensional indicator of economic progress is gross domestic product (GDP). Note, however, that many argue that GDP is insufficient to be used as a sustainability indicator, because it measures economic productivity in areas that would not be considered in a vision of a more sustainable world (e.g., economics of prisons, pollution control, and cancer treatment).

While the Principles of Green Engineering provide a framework for designers, many engaged in sustainability efforts also develop metrics or indicators to monitor their progress in meeting sustainability goals. A **sustainability indicator** measures the progress toward achieving a goal of sustainability. Sustainability indicators should be a collection of indicators that represent the multidimensional nature of sustainability, considering environmental, social, and economic facets. In terms of campus sustainability indicators, the University Leaders for a Sustainable Future (ULSF, 2008) states that “Sustainability implies that the critical activities of a higher education institution are (at a minimum) ecologically sound, socially just and economically viable, and that they will continue to be so for future generations.” Table 1.4 provides a
comparison of traditional versus sustainability indicators for a community, and what new information they provide about progress toward sustainability that is not captured by more traditional indicators (Hart, 2007).

Several quantitative sustainability metrics are heavily utilized by engineers. One of these metrics is the efficiency factor (or \( E \) factor), which is a measure of material efficiencies, that is, the waste generation for materials. While efficiencies of all types have always been a component of good design, the generation of waste, particularly

### Table 1.4

<table>
<thead>
<tr>
<th>Economic indicators</th>
<th>Traditional</th>
<th>Sustainable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Median income</td>
<td>Number of hours of paid employment at the average wage required to support basic needs</td>
</tr>
<tr>
<td></td>
<td>Per capita income relative to the U.S. average size of the economy as measured by gross national product (GNP) and GDP</td>
<td>Dollars spent in the local economy that pay for local labor and local natural resources</td>
</tr>
<tr>
<td></td>
<td>Ambitious financial risk profile</td>
<td>Percent of local economy based on renewable local resources</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emphasis of sustainability indicator</th>
<th>What wage can buy</th>
<th>Defines basic needs in terms of sustainable consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Local financial resilience</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Environmental indicators</th>
<th>Traditional</th>
<th>Sustainable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ambient levels of pollution in air and water</td>
<td>Use and generation of toxic materials (both in production and by end user)</td>
</tr>
<tr>
<td></td>
<td>Tons of solid waste generated</td>
<td>Vehicle miles traveled</td>
</tr>
<tr>
<td></td>
<td>Cost of fuel</td>
<td>Percent of products produced that are durable, repairable, or readily recyclable or compostable</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Total energy used from all sources</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ratio of renewable energy used at renewable rate to nonrenewable energy</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emphasis of sustainability indicator</th>
<th>Measuring activities causing pollution</th>
<th>Conservative and cyclical use of materials</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Use of resources at sustainable rate</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Social indicators</th>
<th>Traditional</th>
<th>Sustainable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Number of registered voters</td>
<td>Number of voters who vote in elections</td>
</tr>
<tr>
<td></td>
<td>SAT and other standardized-test scores</td>
<td>Number of voters who attend town meetings</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Number of students trained for jobs that are available in the local economy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Number of students who go to college and come back to the community</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Emphasis of sustainability indicator</th>
<th>Participation in democratic process</th>
<th>Ability to participate in the democratic process</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Matching job skills and training to needs of the local economy</td>
<td></td>
</tr>
</tbody>
</table>

hazardous waste, can be considered a design flaw. As given in Equation 1.1 (and demonstrated in Example 1.4), the E factor measures the efficiency of various chemical industries in terms of the kilograms of material inputs relative to the kilograms of final product (Sheldon, 2007). It does not consider chemicals or materials that are not directly involved in the synthesis, such as solvents and rinse water. A higher value for the E factor means more waste is produced and thus there is a greater potential for adverse impact on human health and the environment. Manufacturers would thus strive to develop processes where the E factor approaches zero:

$$E \text{ factor} = \frac{\sum \text{kg inputs}}{\sum \text{kg product}}$$ (1.1)

**example / 1.4 Determining the E Factor**

Calculate the E factor for the desired product, given the following chemical production process:

$$\text{CH}_3\text{CH}_2\text{CH}_2\text{OH} + \text{NaBr} + \text{H}_2\text{SO}_4 \rightarrow \text{CH}_3\text{CH}_2\text{CH}_2\text{Br} + \text{NaHSO}_4 + \text{H}_2\text{O}$$

Table 1.5 provides details about the molecules involved.

<table>
<thead>
<tr>
<th>Type</th>
<th>Molecular Formula</th>
<th>Molecular Weight</th>
<th>Weight (g)</th>
<th>Moles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactant</td>
<td>CH$_3$CH$_2$CH$_2$OH</td>
<td>74.12</td>
<td>0.8 (added)</td>
<td>0.80 (added)</td>
</tr>
<tr>
<td>Reactant</td>
<td>NaBr</td>
<td>102.91</td>
<td>1.33 (added)</td>
<td>1.33 (added)</td>
</tr>
<tr>
<td>Reactant</td>
<td>H$_2$SO$_4$</td>
<td>98.08</td>
<td>2.0 (added)</td>
<td>2.0 (added)</td>
</tr>
<tr>
<td>Desired product</td>
<td>CH$_3$CH$_2$CH$_2$Br</td>
<td>137.03</td>
<td>1.48</td>
<td>0.011</td>
</tr>
<tr>
<td>Auxiliary</td>
<td>NaHSO$_4$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auxiliary</td>
<td>H$_2$O</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**solution**

$$E \text{ factor} = \frac{\sum \text{kg inputs}}{\sum \text{kg product}}$$

$$E \text{ factor} = \frac{0.0008 + 0.00133 + 0.002}{0.00148} = 2.8$$

In this example, 2.8 times more mass of material inputs are required than are obtained in the final product. This is not close to the value of zero we would want to set as a goal if the company had zero waste as a sustainability goal.

According to Sheldon, the current bulk chemical industries have E factors of less than 1–5, compared with 5 to greater than 50 for fine chemicals, and 25 to more than 100 for pharmaceuticals. This shows that today there is great opportunity to reduce waste production during chemical manufacturing.

Be aware also that this type of calculation is only a measure of mass efficiency and does not consider the toxicity of the materials used or generated (see Chapter 6 for more information on toxicity and hazard).
1.5 Policies Driving Green Engineering and Sustainability

There is a close, albeit often unrecognized, link between policy and engineering design. **Policies** are plans or courses of action, as of a government or other organization, intended to influence and determine decisions, actions, and other matters. Governmental policies are often aimed at protecting the public good in much the same way that green chemistry and green engineering are aimed at protecting human health and the environment. Policy can be a powerful driver influencing engineering design in terms of which material and energy sources are used through subsidies and/or strict regulations on emissions. In this way, policy can play a significant role in supporting engineering design for sustainability. There are two main types of policies that can affect design at this scale: regulations and voluntary programs.

1.5.1 REGULATIONS

A **regulation** is a legal restriction promulgated by government administrative agencies through rulemaking supported by a threat of sanction or a fine. While there are traditional environmental regulations focused on end of pipe releases, there is an emerging policy area focused on sustainable design. Two of the most established examples include extended product responsibility (EPR) initiatives and banning specific substances.

Extended product responsibilities, such as the European Union’s (EU) Waste Electrical and Electronic Equipment directive, hold the original manufacturer responsible for their products throughout the life cycle. This directive aims to minimize the impact of electrical and electronic goods on the environment by increasing reuse and recycling and reducing the amount of electrical and electronic equipment going to landfills. It seeks to achieve this by making producers responsible for financing the collection, treatment, and recovery of waste electrical equipment and by obliging distributors (sellers) to allow consumers to return their waste equipment free of charge. This drives engineers to design electrical and electronic equipment with the Principles of Green Engineering. For example, these designs consider end-of-life management and aim for ease of disassembly, recovery of complex components, and minimized material diversity. One positive impact of this approach from a company’s perspective is that it reconnects the consumer with the manufacturer at the end-of-the-life, life stage.

Another policy approach to driving engineering design toward sustainability goals is banning specific substances of concern. An example closely tied to the Electrical and Electronic Equipment directive is the EU’s Restriction of Hazardous Substances (RoHS). RoHS is focused on “the restriction of the use of certain hazardous substances in electrical and electronic equipment.” This Directive
bans the placing on the EU market of new electrical and electronic equipment containing more than agreed levels of lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyl (PBB), and polybrominated diphenyl ether (PBDE) flame retardants. By banning these chemicals of concern in significant levels, this directive is driving the implementation of green chemistry and green engineering principles in terms of designing alternative chemicals and materials that reduce or eliminate the use and generation of hazardous substances and preventing pollution.

1.5.2 VOLUNTARY PROGRAMS

Another policy strategy for encouraging green engineering design is through voluntary programs. Voluntary programs are not mandated by law or enforceable, but are meant to encourage and motivate desirable behaviors. The government, industry, or third-party nongovernmental organizations can sponsor these programs. While there are many different varieties of voluntary programs, two types that have been established with success are eco-labeling and preferential purchasing.

Environmental standards allow for an environmental assessment of a product’s impact on factors such as air pollution, wildlife habitat, energy, natural resources, ozone depletion and global warming, and toxic contamination. Companies that meet environmental standards for their specific product or service can apply an eco-label. Eco-labels attempt to provide an indicator to consumers of the product’s environmental performance (e.g., “recycled packaging” or “no toxic emissions”). Independent third parties, such as Green Seal, United States Green Buildings Council, and EnergyStar, provide nonbiased verification of environmental labels and certifications and are the most reliable originators of eco-labels.

First-party eco-labels are self-awarded, and so are not independently verified. In the United States, these sorts of labels are governed by the Federal Trade Commission’s (FTC) guide for the use of environmental marketing claims and must be accurate. The FTC has brought action against several manufacturers for violating truth-in-advertising laws.

To further support these programs, many organizations are implementing environmentally preferable or preferential purchasing policies. These policies can be implemented by any organization (even your college and university!) and mandate a preference to purchase products from office supplies to computers to industrial chemicals with improved environmental and human health profiles. By specifying purchases of this type, organizations are creating a demand in the marketplace for products and services with reduced impacts on human health and the environment, a very powerful tool to drive innovation in this area and to reduce costs of these products through economies of scale. Companies highlighted in the EPA report, “Private Sector Pioneers: How Companies Are Incorporating Environmentally Preferable Purchasing” (EPA, 1999), have achieved a variety of savings as given in Table 1.6.

<table>
<thead>
<tr>
<th>Savings Realized from Environmentally Preferential Purchasing Programs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduced material costs for manufacturers</td>
</tr>
<tr>
<td>Reduced repair and replacement costs when using more durable and repairable equipment</td>
</tr>
<tr>
<td>Reduced disposal costs by generating less waste</td>
</tr>
<tr>
<td>Improved product design and performance of the product(s)</td>
</tr>
<tr>
<td>Increased employee safety and health at the facility</td>
</tr>
</tbody>
</table>
As noted in the EPA report on environmental preferential purchasing, many companies adopted environmental purchasing policies for traditional business reasons as listed in Table 1.7. Although these reasons result in intangible benefits, there are specific examples of measurable reduced costs associated with environmentally preferable products. These include a lower purchase price (e.g., remanufactured products), reduced operational costs (e.g., energy efficiency), reduced disposal costs (e.g., more durable products), and reduced hazardous management costs (e.g., less toxic products). In addition, purchasing environmentally preferable products may reduce an organization’s potential future liability, improve the work environment, and minimize risks to workers.

### Table 1.7

**Environmental Purchasing Policies Align with Traditional Business Metrics**

| Recognizing market preferences and serving customers who have a stated interest in “environmentally friendly” products and practices |
| Distinguishing a company and its products from competitors |
| Avoiding hidden costs and pursuing cost savings |
| Increasing operating efficiency |
| Joining an industry or international market trend |

### 1.6 Designing Tomorrow

By considering the fundamental concepts of sustainability, engineers can contribute to addressing the challenges traditionally associated with economic growth and development. This new awareness provides the potential to design a better tomorrow—one in which our products, processes, and systems are more sustainable including being inherently benign to human health and the environment, minimizing material and energy use, and considering the entire life cycle.

#### Key Terms

- biomimicry
- Brundtland Commission
- carrying capacity
- Carson, Rachel
- causal loop diagram (CLD)
- Code of Federal Regulations (CFR)
- design
- eco-label
- efficiency factor (E factor)
- environmentally preferable or preferential purchasing
- Environmental Protection Agency (EPA)
- extended product responsibility (EPR)
- functional unit
- green chemistry
- green engineering
- indicator
- life cycle
- life cycle assessment (LCA)
- life cycle stages
- life cycle thinking
- *The Limits to Growth*
- materials flow analysis (MFA)
- Millennium Development Goals (MDGs)
- nonpoint source emissions
- Path Forward
- pillars of sustainability
- policies
- Principles of Green Engineering
- regulations
- regulatory process
- resilience
- sustainable development
- sustainable engineering
- sustainability
- sustainability indicator
- systems thinking
- Tragedy of the Commons
- triple bottom line
- urban metabolism
- voluntary programs
1.1 Write an official one-page office memo to your instructor that provides definitions for: (a) sustainable development (by the Bruntland Commission), (b) sustainability (according to the American Academy of Environmental Engineers (AAEE) Body of Knowledge), (c) sustainability (according to the American Society of Civil Engineers (ASCE) Body of Knowledge), and (d) sustainable development (according to the National Society of Professional Engineers (NSPE) Code of Ethics).

1.2 Write your own definition of sustainable development as it applies to your engineering profession. Explain its appropriateness and applicability in two to three sentences.

1.3 Identify three definitions of sustainability from three sources (e.g., local, state, or federal government; industry; environmental organization; international organization; financial or investment organization). Compare and contrast those definitions with the Brundtland Commission definition. How do the definitions reflect their sources?

1.4 Relate the “Tragedy of the Commons” to a local environmental issue. Be specific about what you mean in terms of the “commons” for this particular example, and carefully explain how these “commons” are being damaged for current and future generations.

1.5 Research the progress that two countries of your choice (or your instructor’s choice) have made in meeting each of the eight MDGs. Summarize the results in a table. Among other sources, you might consult the UN’s MDG web site, www.un.org/millenniumgoals/.

1.6 Go to the U.S. Department of Energy’s web site (www.doe.gov) and research energy consumption in the household, commercial, industrial, and transportation sectors. Develop a table on how this specific energy consumption relates to the percent of U.S. and global CO₂ emissions. Identify a sustainable solution for each sector that would reduce energy use and CO₂ emissions.

1.7 As a consumer interested in reducing your carbon emissions, (a) which should you do: (1) install more efficient lighting for your home, or (2) buy a car that gets more miles per gallon? To answer this, consider that a 100 W light bulb that is run 3 h a day every day will use around 100 kWh a year. A high-efficiency light uses about 25 percent of a conventional light bulb. Replacing it with a 25 W compact fluorescent bulb would save 75 kWh a year. This would equal 150 lb of carbon dioxide or the same amount of carbon dioxide emissions associated with burning 7.5 gallons of gasoline. (b) Given that the average U.S. household uses 10,000 kWh a year of which 8.8 percent is lighting, how many gallons of gas and pounds of CO₂ could be saved by switching all of the bulbs in a home? (c) For comparison, if you drove 12,000 miles a year and upgraded from a car that gets the national average of 20 miles per gallon (mpg) to one that got 30 mpg, how much would you reduce your gas consumption and CO₂ emissions on an annual basis? (d) What if you upgraded to a car that gets 30–37 mpg? (Combustion of 100 gallons of gasoline releases 2,000 lb of carbon dioxide.)

1.8 Visit EPA’s Presidential Green Chemistry Challenge Award web site at www.epa.gov/greenchemistry/pubs/pgcc/past.html. Select a past award-winning project. Based on the description of this project, what are the environmental, economic, and social benefits of this green chemistry advance?

1.9 Discuss whether shoe A (leather) or shoe B (synthetic) is better for the environment based on the data given in Table 1.8. Is it possible to weight one aspect (air, water, land pollution, or solid waste) as being more important than another? How? Why? Who makes these decisions for our society?

1.10 To compare plastic and paper bags in terms of acquisition of raw materials, manufacturing and processing, use, and disposal, we will use data provided by Franklin Associates, a nationally known consulting firm whose clients include the U.S. EPA as well as many companies and industry groups. In 1990, Franklin Associates compared plastic bags to paper bags in terms of their energy and air/water emissions in manufacture, use, and disposal. Table 1.9 presents the results of their study.

(a) Which bag would you choose if you were most concerned about air pollution? (Note that the information does not tell you whether these are toxic air emissions or greenhouse gas emissions.) (b) If you assume that two plastic bags equal one paper bag,
1.11 You are preparing a life cycle analysis of three different electrification options for powering your 1,200 ft² home in rural Connecticut. The options you are considering include: (1) just using your local grid, (2) putting a solar installation on your roof, or (3) building a transmission extension to join up with your neighbor’s already-built wind turbine. Write a possible goal, scope, function, and functional unit for this LCA. Explain your reasoning.

1.12 Consider the full life cycle of each of the three electrification options (possibly beyond whatever you have selected for the scope of your LCA) in Problem 1.11. Discuss which of the life cycle stages is most impactful for each electrification type. You will need to take into account the life cycle impacts of primary through final energy in each case. As a reminder, life cycle stages typically include resource extraction, manufacture, transportation, use, and end of life.

1.13 Draw CLD for corn-based ethanol production using the following variables: climate change, corn-based ethanol use, fertilizer demand, CO₂ emissions, fuel demand, fossil fuel use, and corn demand.

1.14 (a) Is centralized drinking water treatment and distribution more resilient than point of use water treatment technologies? Why, or why not? (b) Does it matter whether these water treatment systems are implemented in the developing or developed world?

1.15 The design team for a building project was formed at your company last week, and they have already held two meetings. Why is it so important for you to get involved immediately in the design process?

1.16 Provide an example of a product either commercially available or currently under development that uses biomimicry as the basis for its design. Explain how the design is mimicking a product, process, or system found in nature.

1.17 Two reactants, benzyl alcohol and tosyl chloride, react in the presence of an auxiliary, triethylamine, and the solvent toluene to produce the product sulfonate ester (Table 1.10). (a) Calculate the E factor for the reaction. (b) What would happen to the E factor if the solvents and auxiliary chemicals were included in the calculation? (c) Should these types of materials and chemicals be included in an efficiency measure? Why, or why not?

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### Table 1.8

<table>
<thead>
<tr>
<th>Product</th>
<th>Energy Use (BTU)</th>
<th>Raw Material Consumption</th>
<th>Water Use (gallons)</th>
<th>Air Pollution (lb)</th>
<th>Water Pollution</th>
<th>Hazardous and Solid Waste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoe A (leather)</td>
<td>1</td>
<td>Limited supply; some renewable</td>
<td>2</td>
<td>4</td>
<td>2 lb organic chemicals</td>
<td>2 lb hazardous sludge</td>
</tr>
<tr>
<td>Shoe B (synthetic)</td>
<td>2</td>
<td>Large supply; not renewable</td>
<td>4</td>
<td>1</td>
<td>8 lb inert inorganic chemicals</td>
<td>1 lb hazardous sludge; 3 lb nonhazardous sludge</td>
</tr>
</tbody>
</table>

### Table 1.9

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials manufacture, product manufacture, product use</td>
<td>0.0516</td>
<td>0.0146</td>
<td>905</td>
<td>464</td>
</tr>
<tr>
<td>Raw materials acquisition, product disposal</td>
<td>0.0510</td>
<td>0.0045</td>
<td>724</td>
<td>185</td>
</tr>
</tbody>
</table>
1.18 Choose three of the Principles of Green Engineering. For each one, (a) explain the principle in your own words; (b) find an example (commercially available or under development), and explain how it demonstrates the principle; and (c) describe the associated environmental, economic, and societal benefits, identifying which ones are tangible and which ones are intangible.

1.19 (a) Develop five sustainability metrics or indicators for a corporation or an industrial sector analogous to those presented for communities in Table 1.4. (b) Compare them with traditional business metrics or indicators. (c) Describe what new information can be determined from the new sustainability metrics or indicators.

1.20 A car company has developed a new car, ecoCar, that gets 100 mpg, but the cost is slightly higher than cars currently on the market. What type of incentives could the manufacturer offer or ask Congress to implement to encourage customers to buy the new ecoCar?

1.21 Do you agree or disagree with the following statement? Explain why, or why not, in three to five sentences. “Technology-forcing pollution regulations are preferable to standards- or outcome-based regulations.”

1.22 You are about to buy a car that will last 7 years before you have to buy a new one, and Congress has just passed a new tax on greenhouse gases. Assume a 5 percent annual interest rate. You have two options: (a) Purchase a used car for $12,000, upgrade the catalytic converter at a cost of $1,000, and pay a $500 annual carbon tax. This car has a salvage value of $2,000. (b) Purchase a new car for $16,500 and pay only $100 annually in carbon tax. This car has a salvage value of $4,500. Based on the annualized cost of these two options, which car would you buy?
References


