Basic Principles and Calculations in Chemical Engineering

Ninth Edition

David M. Himmelblau • James B. Riggs

International Series in the Physical and Chemical Engineering Sciences

Force Equivalents

	newtons (N)	pound force (lb_f)
newtons (N)	1	0.2248
pound force (lb_f)	4.448	1

Energy Equivalents

	joule	calorie	kWh	Btu	ft lb_f	hp h
joule	1	0.2390	2.778×10^{-7}	9.478×10^{-4}	0.7376	3.725×10^{-7}
calorie	4.184	1	1.162×10^{-6}	3.97×10^{-3}	3.086	1.558×10^{-6}
kWh	3.6×10^{6}	8.606×10^{5}	1	3412.14	2.655×10^{6}	1.341
Btu	1055	252	2.930×10^{-4}	1	778.16	3.930×10^{-4}
ft lb_f	1.356	0.3241	3.766×10^{-7}	1.285×10^{-3}	1	5.051×10^{-7}
hp h	2.685×10^{6}	6.416×10^{5}	0.7455	2545	1.98×10^{6}	1

Power Equivalents

	$J\ s^{-1}$	kW	ft lb_f s^{-1}	Btu s^{-1}	hp
$J\ s^{-1}$	1	10^{-3}	0.7376	9.478×10^{-4}	1.341×10^{-3}
kW	1000	1	737.56	0.9478	1.341
ft lb_f s^{-1}	1.356	1.356×10^{-3}	1	1.285×10^{-3}	1.818×10^{-3}
Btu s^{-1}	1055	1.055	778.16	1	1.415
hp	745.7	0.7457	550	0.7068	1

Pressure Equivalents

	mm Hg	in. Hg	kPa	atm	bar	psia
mm Hg	1	0.03937	0.1333	1.316×10^{-3}	1.333×10^{-3}	0.01934
in. Hg	25.4	1	3.386	0.03342	0.03386	0.4912
kPa	7.502	0.2954	1	9.869×10^{-3}	0.01	0.1451
atm	760	29.92	101.3	1	1.013	14.696
bar	750.06	29.53	100	0.9869	1	14.50
psia	51.71	2.036	6.894	0.06805	0.06895	1

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International Series in the Physical and Chemical Engineering Sciences

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BASIC PRINCIPLES AND CALCULATIONS IN CHEMICAL ENGINEERING

NINTH EDITION

David M. Himmelblau
James B. Riggs

Pearson

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Note from the Publisher

This book is published in memory of David M. Himmelblau and James B. Riggs, for their valuable contributions to the field of chemical engineering.

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PREFACE

This book serves as an introduction to the principles and techniques used in the field of chemical engineering as well as biological, petroleum, and environmental engineering. Although the range of subjects deemed to be in the province of chemical engineering has broadened over the last thirty years, the basic principles of this field of study remain the same. This book presents the foundation of specific skills and information that are required for the successful undergraduate and postgraduate study of chemical engineering as well as the professional practice of chemical engineering. Moreover, your remaining chemical engineering classes will rely heavily on the skills that you will develop in this course: your ability to solve abstract problems as well as the application of material and energy balances. The study of the field of chemical engineering can be viewed as a tree with material and energy balances being the trunk and the subjects of thermodynamics, fluid flow, heat transfer, mass transfer, reactor kinetics, process control, and process design being the branches off the trunk. From this perspective, it is easy to see the importance of mastering the material that follows.

The primary objective of this book is to teach you how to systematically formulate and solve material and energy balance problems. More important, you should learn to systematically formulate and solve all types of problems using the methods presented in this text. In addition, this text introduces you to the breadth of processes that chemical engineers work with, from the types of processes found in the refining and chemical industries to those found in bioengineering, nanoengineering, and the microelectronics industries. While the analysis used in this book is based largely on a macroscopic scale (i.e., representing a complex system as a uniform system), your later engineering courses will teach you how to formulate microscopic material and energy balances that can be used to more completely describe these systems. In fact, you will learn in these classes that to formulate a microscopic balance you only have to apply the balances presented in this textbook to a very small volume inside the process of interest.

This text is organized as follows:

- Part I, Introduction: Background information (Chapters 1–2)
- Part II, Material Balances: How to formulate and solve material balances (Chapters 3–5)
- Part III, Gases, Vapors, and Liquids: How to describe gases and liquids (Chapter 6–7)
- Part IV, Energy Balances: How to formulate and solve energy balances (Chapters 8–9)
- Part V, Unsteady-State Material and Energy Balances: How to use a macroscopic approach to describe the behavior of unsteady-state systems (Chapters 10–11)
- Additional material is available online: Chapters 12–14 and Appendixes E–M; go to informit.com/title/9780137327171 and register your product to access these materials

Expecting to absorb the information and skills in this text by reading and listening to lectures is a bit naïve. It is well established that one learns by doing, that is, applying what you have been exposed to. In this regard, our text offers a number of resources to assist you in this endeavor. Probably the most important resources for your study of this material are the Self-Assessment Tests at the end of each section in the book. In particular, the Self-Assessment questions and problems are particularly valuable because by answering them and comparing your answers to the answers that follow, you can determine what it is that you do not fully understand, which is quite an important piece of information.

This edition was written with MATLAB and Python integrated into the text. MATLAB and Python codes are presented for solving systems of linear equation, determining the number of independent equations in a system of linear equations, solving a single nonlinear equation, applying cubic spline interpolation to a set of nonlinear data, and integrating initial value ordinary differential equations. In each case, the built-in functions used to accomplish these tasks are presented and described in a standalone fashion.

It is our sincere hope that this textbook and materials not only inspire you to continue to pursue your goal to become a chemical engineer but also make your journey toward that goal easier.

Jim Riggs
Austin, Texas
November 2021

HOW TO USE THIS BOOK

Welcome to *Basic Principles and Calculations in Chemical Engineering, Ninth Edition*. Several tools exist in the book in addition to the basic text to aid you in learning its subject matter. We hope you will take full advantage of these resources.

Learning Aids

1. Numerous examples worked out in detail to illustrate the basic principles
2. A consistent strategy for problem solving that can be applied to any problem
3. Figures, sketches, and diagrams to provide a detailed description and reinforcement of what you read
4. At the beginning of each chapter, a list of the specific objectives to be reached
5. Self-Assessment Tests at the end of each section with answers so that you can evaluate your progress in learning
6. A large number of problems at the end of each chapter with answers provided in Appendix D
7. Appendixes containing data pertinent to the examples and problems
8. Supplementary references for each chapter
9. A glossary at the end of each chapter

Scan through the book now to locate these features.

Good Learning Practices (Learning How to Learn)

You cannot put the same shoe on every foot.
—Publilius Syrus

Those who study learning characteristics and educational psychologists say that almost all people learn by practicing and reflecting, and not by watching and listening to someone else telling them what they are supposed to learn. "Lecturing is not teaching and listening is not learning." You learn by doing.

Learning Involves More than Memorizing

Do not equate memorizing with learning. Recording, copying, and outlining notes or the text to memorize problem solutions will be of little help in really understanding how to solve material and energy balance problems. Practice will help you to be able to apply your knowledge to problems that you have not seen before.

Adopt Good Learning Practices

You will find that skipping the text and jumping to equations or examples to solve problems may work sometimes but in the long run will lead to frustration. Such a strategy is called "formula-centered" and is a very poor way to approach a problem-solving subject. By adopting it, you will not be able to generalize, each problem will be a new challenge, and you will miss the interconnections among essentially similar problems.

Various appropriate learning styles (information processing) do exist; hence you should reflect on what you do to learn and adopt techniques best suited to you. Some students learn through thinking things out in solitary study. Others prefer to talk things through with peers or tutors. Some focus best on practical examples; others prefer abstract ideas. Sketches and graphs used in explanation usually appeal to most people. Do you get bored by going over the same ground? You might want to take a battery of tests to assess your learning style. Students often find such inventories interesting and helpful.

Whatever your learning style, what follows are some suggestions to enhance learning that we feel are appropriate to pass on to you.

Suggestions to Enhance Learning

1. Each chapter in this book will require three or more hours to read, assimilate, and practice your skills in solving pertinent problems. Make allowance in your

schedule so that you will have read the pertinent material **before** coming to class. Instead of sitting in class and not fully understanding what your professor is discussing, you will be able to raise your understanding to a much higher level. It is not always possible, but it is one of the most efficient ways to spend your study time.

2. If you are enrolled in a class, work with one or more classmates, if permitted, to exchange ideas and discuss the material. But do not rely on someone to do your work for you.
3. Learn every day. Keep up with the scheduled assignments—don't get behind, because one topic builds on a previous one.
4. Seek answers to unanswered questions right away.
5. Employ active reading; that is, every five or ten minutes, stop for one or two minutes and summarize what you have learned. Look for connecting ideas. Write a summary on paper if it helps.

Suggestions for How to Use This Book Effectively

How can you make the best use of this book? Read the objectives before and after studying each section. Read the text, and when you get to an example, first cover up the solution and try to solve the stated problem. Some people, those who learn by reading concrete examples, might look at the examples first and then read the text. After reading a section, solve the self-assessment problems at the end of the section. The answers follow. After completing a chapter, solve a few of the problems listed at the end of the chapter. R. P. Feynman, the Nobel laureate in physics, made the point: "You do not know anything until you have practiced." Whether you solve the problems using hand calculators or computer programs is up to you, but use a systematic approach to formulating the information leading to a proper solution.

This book functions as a savings account—what you put in, you get out, with interest.

Register your copy of *Basic Principles and Calculations in Chemical Engineering, Ninth Edition*, on the InformIT site for convenient access to updates and/or corrections as they become available. To start the registration process, go to informit.com/register and log in or create an account. Enter the product ISBN (9780137327171) and click Submit. Look on the Registered Products tab for an Access Bonus Content link next to this product, and follow that link to access any available bonus materials. If you would like to be notified of exclusive offers on new editions and updates, please check the box to receive email from us.

ACKNOWLEDGMENTS

We are indebted to many former teachers, colleagues, and students who directly or indirectly helped in preparing this book, and in particular the present edition of it. We want to thank Professor C. L. Yaws for his kindness, and discussions with Professor Terry Ring and Professor Clayton Radke were helpful for the development of this edition. Far too many instructors using the text have contributed their corrections and suggestions to list them by name. Any further comments and suggestions for improvement of this textbook would be appreciated.

Jim Riggs

The publisher thanks reviewer Vivek Utgikar, who assisted in the publication of this edition.

ABOUT THE AUTHORS

David M. Himmelblau was the Paul D. and Betty Robertson Meek and American Petrofina Foundation Centennial Professor Emeritus in Chemical Engineering at the University of Texas, where he taught for 42 years. He received his B.S. from MIT in 1947 and his Ph.D. from the University of Washington in 1957. He was the author of 11 books and over 200 articles on the topics of process analysis, fault detection, and optimization, and served as President of the CACHE Corporation (Computer Aids for Chemical Engineering Education), as well as Director of the AIChE. His book, *Basic Principles and Calculations in Chemical Engineering,* has been recognized by the American Institute of Chemical Engineers as one of the most important books in this field.

James B. Riggs earned his B.S. in 1969 and his M.S. in 1972, both from the University of Texas at Austin. In 1977, he earned his Ph.D. from the University of California at Berkeley. Dr. Riggs was a university professor for 30 years, the first five years being spent at West Virginia University and the remainder at Texas Tech University. In addition, he had more than five years of industrial experience in a variety of capacities. His research interests centered on advanced process control and process optimization. During his academic career he served as an industrial consultant and founded the Texas Tech Process Control and Optimization Consortium, which he directed for 15 years. Dr. Riggs authored several other popular undergraduate chemical engineering textbooks: *Computational Methods for Chemical Engineers, Programming with MATLAB for Engineers,* and *Chemical and Bio-Process Control, Fifth Edition.*

Dr. Vivek Utgikar (reviewer) is a professor of chemical engineering in the Department of Chemical and Biological Engineering at the University of Idaho. He has also served as the director of the Nuclear Engineering program and the associate dean of Research and Graduate Education for the College of Engineering at the University of Idaho. Dr. Utgikar has an extensive teaching portfolio that includes a broad range of fundamental and advanced engineering courses such as transport phenomena, kinetics, thermodynamics, energy storage, electrochemical engineering, hydrogen, and spent nuclear fuel disposition/management. His research interests include advanced energy systems, nuclear fuel cycle, modeling of multiphase systems, and bioremediation. He was a National Research Council associate at the National Risk Management Research Laboratory of the US Environmental Protection Agency in Cincinnati, Ohio, prior to joining the University of Idaho. Dr. Utgikar is a registered professional engineer with process development, design, and engineering experience in the chemical industry and holds a PhD in chemical engineering from the University of Cincinnati. His other degrees include bachelor's and master's degrees in chemical engineering from Mumbai University, India. He is the author of *Fundamental Concepts and Computations in Chemical Engineering* and *Chemical Processes in Renewable Energy Systems*, both from Pearson.

PART I

INTRODUCTION

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CHAPTER 1

Introduction to Chemical Engineering

Chapter Objectives

- Have a general knowledge of the evolution of chemical engineering.
- Understand what chemical engineering is and the types of jobs chemical engineers perform.
- Appreciate some of the issues associated with sustainability and green engineering.
- Understand the importance of ethics in the practice of engineering.

Introduction

Chemical engineers deal with processes that convert raw materials into useful products. Many times, these processes involve reactions followed by purification of the products, such as chemical reactions followed by concentration of the products, biological reactions followed by systems that recover and purify the products, or reactions and recovery of products on a nanometer scale. Overall, chemical engineers are process engineers—that is, chemical engineers deal with processes that produce a wide range of products.

1.1 A Brief History of Chemical Engineering

Chemical engineering evolved from the industrial applications of chemistry and separation science (i.e., the study of separating components from mixtures) primarily in the refining and chemical industry, which we refer to here as the **chemical process industries, CPI**. The first high-volume chemical process was implemented in 1823 in England for the production of soda ash, which was used to produce glass and soap.

In 1887, a British engineer, George E. Davis, presented a series of lectures on chemical engineering that summarized industrial practice in the chemical industry in Great Britain. These lectures stimulated interest in the United States and to some degree led to the formation of the first chemical engineering curriculum at MIT in 1888. Over the next 10 to 15 years, a number of US universities embraced the field of chemical engineering by offering curriculum in this area. In 1908, the American Institute of Chemical Engineers was formed and since has served to promote and represent the interests of the chemical engineering community.

Mechanical engineers understood the mechanical aspects of process operations, including fluid flow and heat transfer, but they did not have backgrounds in chemistry. Conversely, chemists understood chemistry and its ramifications but lacked the process skills. In addition, neither mechanical engineers nor chemists had backgrounds in separation science, which is critically important to the CPI. As a result, the study of chemical engineering evolved to meet these industrial needs.

The acceptance of the "horseless carriage," which began commercial production in the 1890s, created a demand for gasoline that ultimately fueled exploration for oil. In 1901, Patillo Higgins, a Texas geologist, and Anthony F. Lucas, a mining engineer, later to be known as "wildcatters," led a drilling operation that brought in the Spindletop Well just south of Beaumont, Texas. At the time, Spindletop produced more oil than all the other oil wells in the United States. Moreover, a whole generation of wildcatters was born, resulting in a dramatic increase in the domestic production of crude oil, which created a need for larger-scale, more modern approaches to crude refining. As a result, a market developed for engineers who could assist in the design and operation of processing plants for the CPI. The success of oil exploration was to some degree driven by the demand for gasoline for the automobile industry, and ultimately, it led to the widespread adoption of automobiles for the general population due to the resulting lower cost of gasoline.

These early industrial chemists/chemical engineers had few analytical tools available to them and largely depended on their physical intuition to perform their jobs as process engineers. Slide rules were used for performing calculations, and by the 1930s and 1940s, a number of nomographs were developed to assist them in the design and operation analysis of processes for the CPI. Nomographs are charts that provide a concise and convenient means to represent physical property data (e.g., boiling point temperatures or heat of vaporization) and can also be used to provide simplified solutions of complex equations (e.g., pressure drop for flow in a pipe). The availability of computing resources in the 1960s was the beginning of computer-based technology that is commonplace today. For example, since the 1970s, **computer-aided design (CAD) packages** have allowed engineers to design complete processes by specifying only a minimum of information; all the tedious and repetitive calculations are done by the computer in an extremely short period of time, allowing the design engineer to focus on the task of developing the best possible process design.

In 1959, Professors Bird, Stewart, and Lightfoot of the Department of Chemical Engineering at the University of Wisconsin published their textbook *Transport Phenomena* that covered fluid flow, heat transfer, and mass transfer. This book was widely adopted throughout the chemical engineering community and provided a much more mathematical and abstract analysis of these topics than had previously been used. The widespread use of this book ushered in a much more analytical approach to chemical engineering than the more empirical approach that preceded it.

During the period 1960–80, the CPI also made the transition from an industry based on innovation in which the profitability of a company depended to a large degree on developing new products and new processing approaches to a more mature commodity industry in which the financial success of a company depended on making their products using established technology more efficiently, resulting in less expensive products.

Globalization of the CPI markets began in the mid-1980s and led to increased competition. At the same time, development in computer hardware made it possible to apply process automation more easily and reliably than ever before. These automation projects provided improved product quality while increasing production rates and overall production efficiency with relatively little capital investment.

Beginning in the mid-1990s, new areas came on the scene that took advantage of the fundamental skills of chemical engineers, including the microelectronic industry, the pharmaceutical industry, the biomedical industry, and nanotechnology. Clearly, the analytical skills and the process training made chemical engineers ideal contributors to the development of the production operations for these industries. In the 1970s, more than 80% of graduating chemical engineers took jobs with the CPI and government. By 2000, that number had dropped to 50% due to increases in the number taking jobs with biotechnology companies, pharmaceutical/health care companies, and electronics and materials companies.

1.2 Types of Jobs Chemical Engineers Perform

Chemical engineers perform a wide range of jobs. Moreover, during your career, you are likely to have a number of different types of jobs. Following are the general types of jobs that chemical engineers perform:

- **Operations:** Operations engineers, or process engineers, are the first line of technical support for a processing plant. These engineers spend a lot of their time in the plant monitoring the operations and solving operational problems. When a serious technical problem occurs in the middle of the night, the operations engineer for that process is called in to resolve the problem. Many young chemical engineers start out as operations engineers for a few years so that they can become familiar with plant operations before they move to other assignments. This job also provides companies a view of how young engineers handle responsibility as well as how effectively they are able to work with others.
- **Technical sales:** Many products today are highly technical in nature and the consumer of these products often requires technical assistance to fully utilize them. Technical sales engineers provide that service as well as acquire new customers. Obviously, sales engineers need to be able to work effectively with their customers and to fully understand the technical issues associated with their company's products in order to maintain customer satisfaction.
- **Design:** Design is developing something new that meets a defined need and is used to develop new products and services, many times using teams of engineers. Design is a challenging endeavor because there is no limit to how many new ways something can be designed. Therefore, design requires creativity and experience. As a result, design teams often are made up of members with a wide range of experience and training. It is the design team's job to determine the best design for a product considering technical feasibility, economic viability, and the definition of the need for the end user.
- **Consulting:** Consulting companies specialize in specific areas of engineering—safety, design, control, and so on. When an operating company needs a consultant's expertise, it simply contracts with the consulting company for the needed services. Because consulting companies provide technical services on an as-needed basis, the company that hires a consultant does not have to employ an expert in a particular field as a full-time employee. Consulting companies often hire engineers who have many years of engineering experience in specific technical areas. Individuals also serve as industrial consultants after years of experience in industry, academia, or government laboratories.

- **Project management:** Project management engineers are similar to operations engineers in that they are called upon to provide a number of technical services for the day-to-day operation of a project (e.g., an expansion project for a process or the construction of a new process). Initially, these engineers are required to develop estimates of labor and material for the project, and this information is then used to receive approval for the project. The project management engineer is responsible for coordinating the project or a portion of the project when the project is approved. Coordinating the project requires working with a number of parties, e.g., the management team, the construction team, the suppliers, and the operations department in order to deliver a high-quality project on time and on budget.
- **Management: Corporate, operations, and technical:** Many companies use chemical engineers for their corporate management because the position requires technical knowledge. Engineers who move into corporate management usually have training in business or have attended an MBA program. They normally work their way up the management ladder from technical management and operations management positions. Corporate management directs the business at the corporate level and deals with issues such as the corporate image, identifying new business opportunities, and deciding how to handle economic downturns, all in an effort to improve the overall profitability of the corporation. Operations management deals with the day-to-day problems and opportunities associated with operating an industrial production facility. Technical management is concerned with managing engineers who deal with operations, research, and development.
- **Development:** Development teams work with design teams to apply various designs so that they can be further tested. During this phase, the real-world consequences of potential designs become apparent, and the development team is charged with solving these problems when possible. For a new process, a pilot-scale process can be constructed, operated, and monitored to evaluate the performance of the new process (e.g., to determine the activity and yield of a catalyst). In effect, development teams are asked to demonstrate whether a design concept is viable.
- **Research:** Research is the scientific investigation of physical systems using laboratory experiments and/or computer simulations. Fundamental, or "blue-sky," research studies the fundamental behavior of certain systems without regard to a specific industrial problem (e.g., studying the fundamental chemical reactions associated with a class of compounds). Industrial research is research aimed at solving an industrial problem (e.g., developing a new composite material that can

be used in an industrial application). Whenever a technical issue has an important effect on society (e.g., developing green sources of energy), large amounts of government funding are usually offered to researchers, who explore and propose ways to solve these problems.

- **University teaching:** Engineering professors typically have a PhD in engineering or a related field and divide their work effort between research, teaching, and service to the profession. Their research effort is based on fundamental studies of engineering systems, while their teaching relies on being able to effectively communicate abstract material and practical approaches to students in a way that the students can assimilate and apply this information. Engineering professors are evaluated for promotion and advancement on the basis of publications in peer-reviewed journals, their ability to develop research funding, their effectiveness as a teacher, and their contribution to the engineering profession. Being an engineering professor is a demanding profession because of the breadth of work the individual must perform, but it can be a very rewarding career to help young people along the path to becoming successful engineers.

1.3 Industries in Which Chemical Engineers Work

A chemical engineering education exposes the graduate to the fundamentals of process engineering and develops the graduate's ability to deal with complex problems. As such, chemical engineers are ideally suited to work in a wide variety of industries. Figure 1.1 shows the primary areas in which chemical engineers work.

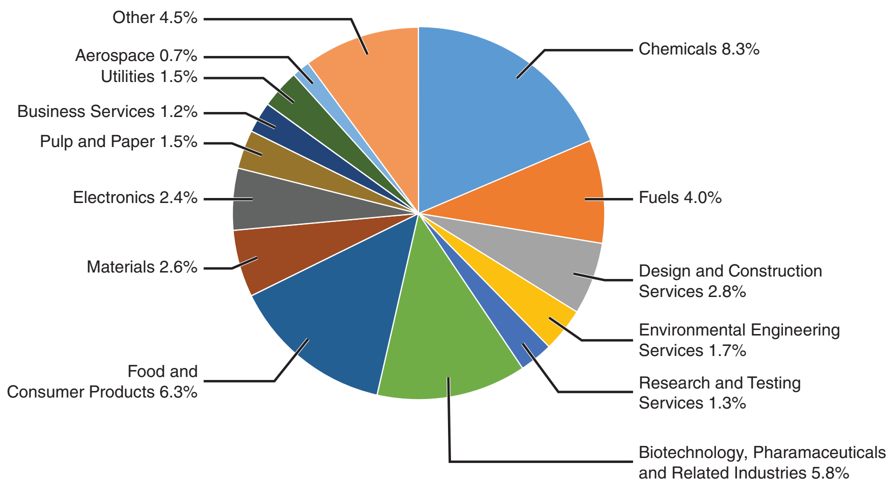

Figure 1.1 The primary areas in which chemical engineers work (Source: AIChE)

Following are brief descriptions of these primary CPI:

- **Refining:** Refining involves processing crude oil to produce fuels and lubrication oils for automobiles, trucks, and airplanes. In addition, refineries produce a wide range of chemical intermediate products, that is, products that serve as feed stocks for other processes (e.g., propylene for a process that produces polypropylene plastics). Refineries are typically large-scale processes having feed rates up to 600,000 barrels of crude oil per day.
- **Chemicals:** The chemical industry can be categorized as producing commodity, specialty, or fine chemical products. Commodity chemicals are high-volume products that are used as feed stocks for other chemical processes. For example, a petrochemical plant, which produces large volumes of chemical intermediates, is usually a part of most large-scale refineries. Specialty chemicals are relatively low-volume products that are often produced in batch operations. Examples of specialty chemicals include certain agricultural chemicals, paint pigments, and special-purpose solvents. Fine chemicals are commodity chemicals that are produced on a relatively small scale and are used as feed stocks for specialty chemicals.
- **Environmental:** Environmental engineers work to ensure that human health and nature's ecosystems are protected from emissions resulting from industry and human activity. Common efforts of environmental engineers include wastewater management, air and water quality control, waste disposal, processing or recycling waste streams, and documentation of these efforts (e.g., required reports to the Environmental Protection Agency [EPA] or environmental impact statements for proposed projects).
- **Equipment design and construction:** This category relates to the design and construction of new processes or expansion projects for existing processes. The design process involves determining the type and sequence of equipment and the sizing of this equipment, and this effort is typically performed by consulting companies that specialize in process design. Once the design is completed, chemical engineers are typically involved during the construction and startup of the process.
- **Pharmaceuticals and health care:** The pharmaceutical industry develops, produces, and markets synthetic drugs that can be administered to patients to treat or alleviate symptoms or protect against disease (e.g., vaccines). These products are usually produced using biological reactions.

- **Biotechnology:** Biotechnology uses living systems by harnessing cellular processes and biomolecular processes to develop products ranging from medicines to fuels to food. Although biotechnology is currently a developing research area, it has been used by humans for thousands of years to make or preserve foods (e.g., beer and wine, bread, and sauerkraut), to improve livestock and plants by selective breeding, and to improve agricultural soils by introducing bacteria that are able to fertilize crops and protect against attacks from insects.
- **Biomedical applications:** Biomedical engineers are involved with the application of engineering principles combined with knowledge of biology and human physiology for health care purposes. Application areas include diagnosis, monitoring, and therapy as well as the development of new technologies, such as artificial tissue and artificial organs.
- **Food production:** Chemical engineers work in a variety of ways for the "farm to fork" food industry, including agrochemicals and food processing, such as making potato chips, granola bars, candy, beer, or yogurt.
- **Government:** Chemical engineers work for certain government regulatory agencies [e.g., EPA or the Occupational, Safety and Health Administration (OSHA)] or government laboratories (e.g., Sandia National Laboratory and the National Institutes of Health).
- **Professional:** This category includes professions (e.g., patent lawyers and medical doctors) that require certification as well as specialized education (e.g., university professors).

1.4 Sustainability

A **sustainable product** is a product that meets the current needs without compromising the ability of future generations to meet their needs while protecting human health and the needs of society. Chemical engineers are ideally suited to evaluate the sustainability of a wide range of products and technologies, and therefore, we present an overview of sustainability and **green engineering** as an example of one of the ways that chemical engineering can contribute to society today and into the future.

Current estimates indicate that the societies of the world are consuming 50% more resources (e.g., energy, water, minerals, the ability to produce food) than the world can sustain (what the population of the world consumes in one year requires 18 months to replenish). The United States consumes natural resources at a rate that is more than 13 times the rate for the rest of the world. With the rapid growth in the economies of China and India, who make up almost 40% of the world's population, the world resource consumption rate is expected to accelerate.

In addition to preserving resources for the future, sustainable engineering involves protecting human health and the needs of society. That is, the effects of pollution and the impact on global warming are factors that also should be considered in any sustainable design project. As a result, a number of engineering professional groups are concerned that sustainability should be an integral part of future designs. That is, sustainability, or at least improved sustainability, should be an objective for engineering design work as opposed to basing design solely on minimum cost or maximum profit without regard to the impact on sustainability. The problem is that a sustainable design will, in general, cost more to implement than its nonsustainable counterpart. Therefore, the challenge for you as a future engineer is to develop new approaches that make sustainability as economically viable as possible.

As an example, consider a sustainable design for a building. The following features are aspects related to a sustainable design of a building:

- Nontoxic construction materials that can be produced from recycled materials using low-energy processing techniques
- Energy efficient design (e.g., low heat transfer rates to or from the building) using materials that require low amounts of energy to produce
- Renewable energy sources (solar panels, solar water heaters, etc.)
- High durability for the building, yielding a long service life; materials that develop character as they age
- Interior and exterior appearance as similar as possible to nature (i.e., producing a soothing environment for humans)
- Designing for a low total carbon footprint (i.e., the total carbon dioxide liberated during the production of the materials used in the building and the process of constructing the building)

- Using biomimicry (i.e., redesigning industrial processes along biological lines to produce building materials)
- Transferring ownership from an individual to a group of people, similar to car sharing
- Employing renewable materials that come from nearby sources

As you can see from this list, the design problem becomes more complicated when a more holistic approach to engineering is used, but on the other hand, this approach creates more opportunities for creative solutions.

1.4.1 Life-Cycle Analysis

A **life-cycle analysis** is a comprehensive method for developing a sustainable design (**green engineering**). A life-cycle analysis not only considers the effect of a product on the environment and on important resources but also considers all the steps used to produce a product and what happens to the product after its useful life has ended. Figure 1.2 shows a schematic example of a life-cycle analysis of a product.

As illustrated in Figure 1.2, raw materials are extracted from the earth, such as minerals and crude oil. These raw materials are refined into useable products, such as metals and chemical products, in a material processing operation. Next, these useable materials are used to manufacture parts of the final product and are assembled into the final product. Then, the product is used for its intended purpose for the life of the product. When the useful life of the product ends, the product must be disposed of and/or recycled. The recycling process recovers all or part of the product and returns the recovered material so that it can be used for other products in the future. Each of these steps, from raw material extraction to recycling materials, in general, requires the use of resources (e.g., energy) and has an environmental impact (e.g., generates pollutants), which is indicated by the two oppositely pointing arrows used in Figure 1.2. That is, each step in the life-cycle analysis generally requires resource consumption and results in pollution generation.

When a life-cycle analysis is used for a sustainable design, all the required resources and all the resulting loads on the environment are considered. Moreover, the effect of the design of the product on the ability of the product to be recycled at the end of life should be considered.

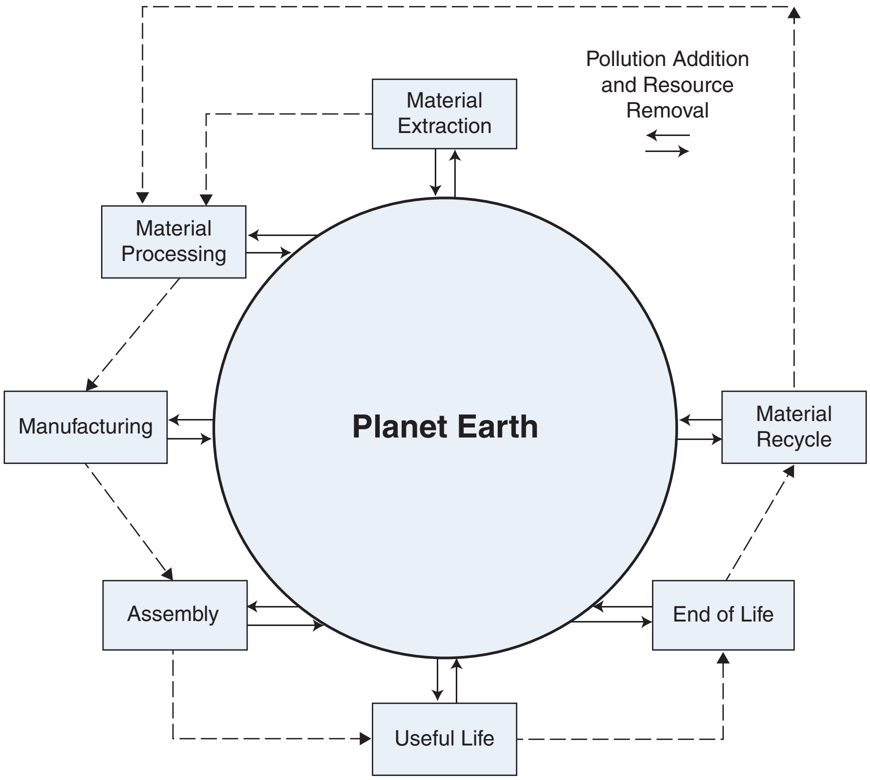

Figure 1.2 Schematic representation of a life-cycle analysis

Now consider how a life-cycle analysis would be applied to the four types of engineering designs: a device, a process, software, and services. The elements of a life-cycle analysis for a typical device are shown in Figure 1.2: The materials that compose the device must be extracted, refined, and manufactured into parts for the device. Then the parts are assembled into the device. And after the useful life is complete, material recycle can be used.

For a process, the elements of a life-cycle analysis closely follow the schematic in Figure 1.2. Moreover, the hardware elements used to implement a process (e.g., vessels, pumps, and processing equipment) are devices so that, with regard to the hardware of the process, the components of the life-cycle analysis are exactly the same as those used for a device. From an overall point of view, the pollution generated and the resources consumed during the useful life of a process would be expected to be the primary factors affecting resources and the environment far exceeding those associated with the hardware.

The life-cycle analysis of software and services is quite different from that of a device or process. In general, the impact of software and services on the resources and the environment is considerably less, although not always insignificant. For example, software that manages the operation of an automobile engine can have a significant effect on the resources and the environment during its useful life, while the development of the software itself would not have a significant effect.

A life-cycle analysis for a product can be simplified by using a database that provides the resource and environmental loads of a number of materials, including metals, plastics, and chemical feedstocks. Such a database eliminates the need to calculate the resource and environmental loads associated with the corresponding extraction and material processing and possibly manufacturing, as shown in Figure 1.2. The US Life Cycle Inventory Database (www.nrel.gov/lci) provides extensive information on metals, plastics, agricultural products, chemical feedstocks, services, and so on. A number of commercial databases are also available.

Example 1.1 Comparison of the Production of Ethanol and Gasoline Based on a Life-Cycle Analysis

Problem Statement

Using a life-cycle analysis, compare ethanol (EtOH) from corn to gasoline as a transportation fuel with regard to greenhouse gas (GHG) generation.

Solution

Figure E1.1 shows schematics of the life-cycle analysis for the production of EtOH from corn and for the production of gasoline as a motor fuel. Note that for the production of EtOH, corn is produced by farming, which requires the use of fertilizers. The corn is used to produce EtOH using a fermentation and recovery process. The primary energy consumption and generation of GHG emissions occurs in the production of the fertilizer, growing the corn, and converting the corn to EtOH. In contrast, gasoline is produced by extracting crude oil from underground formations and refining the crude oil into gasoline and other products such as jet fuel, diesel, and lube oil. For gasoline, the primary energy consumption and generation of GHG emissions occurs during the crude oil production and refining, where refining is the largest contributor.

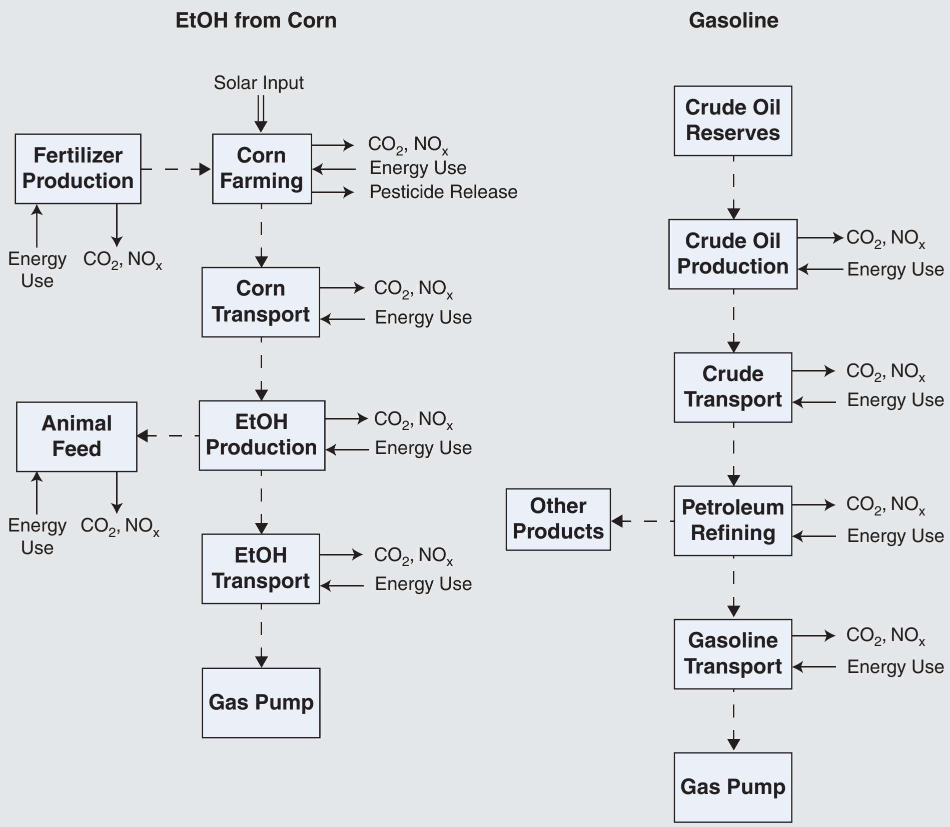

Figure E1.1 Schematic of life-cycle analysis for EtOH from corn and gasoline

From Figure E1.1 you can see that a number of operations must be considered when performing this life-cycle analysis. Moreover, the expertise required to develop a life-cycle analysis for a case like this is expansive, requiring a multidisciplinary team. For example, in order to develop a quantitative life-cycle analysis for EtOH from corn, expertise in agricultural operations, soil science, fermentation, separation science, and process systems is required. The US Department of Energy[1] performed such a life-cycle analysis study and found that EtOH from corn used in motor fuel (i.e., gasohol) reduced GHG emissions by 20%.

[1]J. Han, "Life-Cycle Analysis of Ethanol: Issues, Results and Case Simulations," Annual ACE Conference, Omaha, NE, August 15, 2015.

1.4.2 Materials Sustainability

Materials are a natural part of most design projects. Therefore, it is important to use green, sustainable materials as much as possible. A life-cycle analysis is an excellent method to assess the sustainability of materials used in a project. Following the schematic of a life-cycle analysis shown in Figure 1.2, the initial impact on sustainability is the extraction of the material and its refining. The lower the concentration of a material that is extracted, in general, the more the energy required to refine it. The next key aspect is whether the material directly contributes to the environmental load during the useful life of the product of the design project. For example, certain pesticides can evaporate into the atmosphere and affect human health. And the final aspect is whether the materials can be reused or recycled after the useful life of the product. In summary, **an ideal green material**

- Can be extracted and refined without undue use of resources and without significant environmental emissions.
- Does not contribute to environmental releases during its useful life.
- Can be reused or recycled to a significant degree.

Table 1.1 Mass Abundance of Selected Elements in Earth's Crust[2]

Element	Mass Fr.	Element	Mass Fr.	Element	Mass Fr.
O	46.4%	S	0.03%	Pb	12 ppm
Si	28.2%	C	0.02%	U	2.7 ppm
Al	8.2%	V	0.01%	Sn	2.0 ppm
Fe	5.6%	Cl	0.01%	As	1.8 ppm
Ca	4.1%	Cr	0.01%	Mo	1.5 ppm
Na	2.4%	Ni	75 ppm	W	1.5 ppm
Mg	2.3%	Zn	70 ppm	Bi	0.17 ppm
K	2.1%	Cu	55 ppm	Pd	0.15 ppm
Ti	0.6%	Co	25 ppm	Hg	0.08 ppm
P	0.1%	Li	20 ppm	Ag	0.07 ppm
Mn	0.1%	N	20 ppm	Pt	0.005 ppm
Fl	0.06%	Ga	15 ppm	Au	0.004 ppm

[2] S. R. Taylor, "Trace Element Abundances and the Chondritic Earth Model," *Geochimica et Cosmochimica Acta* 28, no. 12 (1964): 1989–98.

Table 1.1 lists the abundance of selected elements in the earth's crust. Even though gold makes up only 0.004 ppm of the total earth's crust, highly concentrated deposits of gold have been found, thus simplifying its recovery. In contrast, rare earth metals, some of which make up more of the earth's crust than gold, are found only in ores at relatively low concentrations. In terms of sustainability, abundance is only one factor. That is, the abundance and the net consumption from use together determine whether an adequate supply of a material is available. Listed in Table 1.2 are minerals that have been identified as having a limited supply based on their use in 1995.

Table 1.2 Elements with a Limited Supply[3]

Degree of Supply	Elements
Potentially highly limited	Ag, Au, Cu, As, Se, Te, Zn, Cd
Potentially limited	Co, Cr, Mo, Ni, Pb, Pt, Ir

Besides elements, the sustainability of materials that result from plant growth, such as crude oil and lumber, should be considered. For example, the production of lumber results in a removal of GHGs from the atmosphere even though the milling and transportation will generate some GHGs. Of course, the consumption of crude oil, in general, results in significant GHG emissions.

With regard to the availability and supply of a material, as the supply of a material decreases, the market price for that material tends to increase. For example, during the mid-1970s, a shortage of crude oil dramatically increased the price of crude oil and, as a result, the price of gasoline. This price increase for crude stimulated exploration for crude oil as well as conservation efforts. Therefore, by the early 1980s, there was an excess of crude on the market and the price of crude oil dropped dramatically.

Another important natural resource is phosphorus. Before the advent of modern farming practices, farmers used wastes (e.g., compost) to return phosphorus to their soil after their crops consumed it during their growth cycle. Today, most farmers use inorganic phosphate to fertilize their crops. Estimates predict that currently known reserves of phosphate (i.e., a source of phosphorus) will be exhausted in 80 years at the current consumption rate. What this means is that the current phosphate reserves that are easy to extract and refine will be exhausted. Even if new high-quality phosphate

[3] T. E. Graedel and R. R. Allenby, *Industrial Ecology*, Prentice Hall, 1995.

reserves are not identified, an expected increased price of phosphate should drive the processing of lower-quality phosphate reserves and the extraction of phosphorus from waste material. In addition, an increase in the cost of phosphate should also encourage farmers to use their fertilizer more efficiently.

With regard to the elements in Table 1.1 that have been identified as having a potentially limited supply, if the increased consumption of one of these elements begins to reduce its supply, the price of that element would be expected to increase. This increase in price would stimulate increased exploration for it and could possibly make ores that were previously uneconomical to refine financially viable for refining. In addition, the increased price of the material would be expected to increase the recovery from end-of-life products and recycling. During the design phase of a project, the use of a material with a potentially limited supply should be viewed as increasing the overall risk of the project. That is, a material with a potentially limited supply can be susceptible to significant price increases in the future, which could affect the economic viability of a project.

1.4.3 Environmental Releases and Toxicity

The release of chemicals during extraction, refining, use, or end of life can result in a significant environmental load affecting human health or the health of ecosystems.

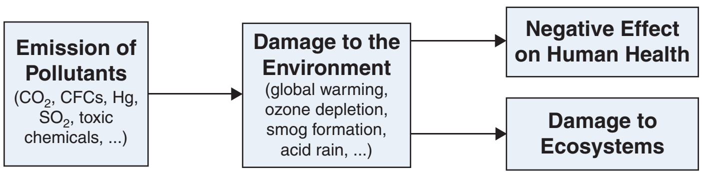

Figure 1.3 Overall effect of the emission of pollutants

Figure 1.3 illustrates the connection between certain emissions (i.e., pollution) and human health and the health of ecosystems. Pollution results in global warming, ozone depletion, smog formation, acid rain, and so on. These in turn affect human health, cause damage to ecosystems, and disrupt human activities (e.g., increased damage from natural disasters). For example, consider the emission of chlorofluorocarbons (CFCs). CFCs damage ozone in the stratosphere, resulting in an increase in UVB radiation on the surface of the earth, which in turn increases skin cancer and the occurrence of cataracts and causes human immune system suppression, crop damage, and damage to marine life.[4]

Roughly 2000 new chemicals are introduced each year, and companies, government agencies, and the public need a method to evaluate the potential risks of these new chemicals. Evaluation is done by using screening tests, and in certain cases, extensive testing is required. That is, screening is used to identify which chemicals have the potential to be environmentally risky, and then extensive testing is used to evaluate those chemical to determine if they, in fact, represent a significant risk to human health and the health of ecosystems.

Table 1.3 outlines an approach used to screen chemicals for environmental risks. The first entry (dispersion and fate) has to do with the tendency of the chemical to accumulate in water, air, soil, and living organisms. The second entry (degradation rates) relates to how quickly the chemical is degraded in water, air, soil, and living organisms. The category "uptake by organisms" is related to specific factors that affect uptake and degradation in organisms while "uptake by humans" considers the rates at which the chemical is able to enter the human body and the rates at which the human body is able to expel it or degrade it into a nontoxic form. "Toxicity and other health effects" has to do with how the level of exposure to the chemical affects the health of organisms and humans.

Table 1.3 Chemical Properties Needed to Perform Environmental Risk Screenings[5]

Aspects Affecting the Environment	Relevant Properties
Dispersion and fate	Volatility, density, melting point, water solubility, soil sorption coefficient, effectiveness of wastewater treatment
Degradation rates in the environment	Atmospheric oxidation rate, aqueous hydrolysis rate, rate of degradation by sunlight, rate of microbial degradation, adsorption
Uptake by organisms	Volatility, the ability to dissolve in fat, molecular size, degradation rate in an organism
Uptake by humans	Transport through the skin, transport rates across lung membrane, degradation rates within the human body
Toxicity and other health effects	Dose–response relationships

[4] D. T. Allen and D. R. Shonnard, *Sustainable Engineering: Concepts, Design, and Case Studies*, Prentice Hall, 2012.

[5] After Allen and Shonnard, *Sustainable Engineering*.

If the screening process determines that a chemical could pose a significant risk to human health or to ecosystems, a detailed assessment of the impact of the chemical on the environment would be required. This assessment would involve testing with a range of laboratory animals with a range of exposure scenarios (e.g., exposure to a single large dose, exposure to multiple smaller doses, and continuous exposure to a low-dose level). The results of these studies may include the degree of reduction in life expectancy as well as the characteristics of the offspring of the laboratory animal.

1.4.4 Principles of Green Engineering

To effectively address the full range of design cases, it is necessary to have a general set of guidelines that, when applied, ensure a sustainable design. A number of guidelines for sustainable design have been developed.[6]

Following is an overview of the key factors identified here as the principles of green engineering, which are based on previous work in this area:

1. **Use energy and material inputs that are as inherently nonhazardous as possible.** Because material and energy input have such an important effect on the sustainability of a product, it is important to ensure that they are as nonhazardous as possible. When hazardous materials are used, special controls and planning for adverse conditions are required, which increases the cost and complexity of a design.
2. **Minimize wastes.** The generation of wastes creates special problems due to the difficulty and cost associated with dealing with wastes, especially hazardous wastes. Therefore, during the design phase, it is important to minimize waste generation. In certain cases, it is possible to find a use for a "waste product," such as using it as a feedstock for another process. For example, during the early days of crude oil refining, natural gas was considered a waste product and was burned into the atmosphere until it was determined that natural gas could be used for heating homes and businesses. In other cases, it may be possible to modify the chemistry of a reaction so that waste products are eliminated or at least significantly reduced.
3. **Minimize energy consumption.** In certain industries (e.g., the refining, petrochemical, and mineral purification industries), the energy usage for purification is a primary operating expense. In these cases, energy usage can be significantly reduced using heat integration, that is,

[6] Allen and Shonnard.

using waste heat (i.e., cooling that is required in the process) from one part of the process to provide heat to another part of the process.

4. **Minimize material usage.** Material usage can be minimized by designing the system or process so that the greatest possible conversion of the feed material to the product is obtained. Material use can also be minimized by extracting the feed components from waste streams so that they can be recycled to the process or using components from waste streams as a feedstock for other processes.
5. **Apply just-in-time manufacturing.** Just-in-time manufacturing is manufacturing that meets the demand for a product precisely when the product is needed, thus eliminating wastes and reducing the need for inventory. In terms of design, this means designing a system or process precisely for the expected demand and completing the project so that the product of the design is available only when the demand is present.
6. **Design for proper durability.** Proper durability means that a product is designed to last for the designed useful life and afterwards can be easily transformed into materials that can be recycled or reused or that can degrade into environmentally benign products.
7. **Design for recycling or reuse after end of life.** Materials can be recycled after end-of-life use by designing the product so that material recycling is simple and easy to implement. For example, scarce materials can be used in a way that facilitates their recovery for recycle. Components of a product can be designed so that they can be used in future generation devices (e.g., parts of a cell phone). Also, products can be designed for reuse (e.g., soft drink bottles).
8. **Use a life-cycle analysis to minimize the environmental impact of the project.** A life-cycle analysis is the most complete way to evaluate the impact of a project on the environment and natural resources. In this manner, the key areas of environmental load and resource depletion can be identified and addressed. For example, if the areas of material extraction and refining are the primary contributors to environmental load and resource depletion for a project, recycling would clearly be the best approach to improve the sustainability of the project.
9. **Use renewable sources of energy and materials.** The use of renewable sources of energy and materials reduces environmental impact and resource depletion. Solar panels are an example of a renewable energy source, and lumber is an example of a renewable material.

10. **Engage both communities and stakeholders in the project.** It is critically important to involve local communities from the conceptual stages through the completion of a design project when the project has any real or perceived impact on the local community. In addition, sustainable goals can sometimes be met by affecting a change in social behavior (e.g., the development of autonomous vehicles so that the use of vehicles is shared).

The principles of green engineering are really a checklist of factors that should be considered during the design process; otherwise, the design can be less sustainable than it could have been.

1.4.5 Optimization and Sustainable Engineering

Each of the principles of green engineering presented here should be applied in a balanced fashion. For example, strictly minimizing the energy consumption may result in an excess use of materials. That is, all the relevant factors, including the impact on the environmental load and ecosystems as well as the material and energy cost, should be considered when optimizing a sustainable design project (i.e., finding the optimal sustainable design).

The conventional approach to optimization of a design project neglecting the impact on the environment and society is to consider the costs associated with the end product of the design along with the expected income generation to identify the optimum design over the life of the product considering the time value of money.

When the impact on the environment and society are considered during the design process, the problem arises that the environmental and the societal impact are not easily represented on a monetary basis. Nevertheless, several different approaches are available for including the impact on the environment and society in the design process.

The most direct means of including the impact on resources and the environment is to follow government regulations. For this case, the government regulations would represent constraints on the design process that have to be satisfied for any valid design. For example, maximum SO_2 emissions are set by EPA regulations for coal-fired electric utilities. While there are certain cases where this approach is valid (e.g., the maximum safe chemical concentrations), it is not feasible to develop government regulations for the full range of factors that affect sustainability. For example, GHG emissions do not lend themselves to explicit limits.

Another approach is to rate products on the basis of their total impact on resources and the environment. For example, new home construction can be rated according to the total resource depletion and total pollution generation. Ratings such as a silver, gold, or platinum can be assigned to a new house based on sustainability and, of course, a platinum rating will command a higher price than a gold rating, which will command a higher price than a silver rating. The success of this approach depends on the judicious selection of the criterion to quality for each classification, taking into account the costs necessary to qualify for each classification and the resulting benefit to resources and the environment. However, not all design projects fit into this approach.

Another approach is to estimate the total cost to society of specific emissions. Total cost to society includes increases in medical costs, lost productivity, and a reduction in life expectancy. For example, the EPA has estimated the total cost to society for CO_2, CH_4, and NO_2 emissions. In this manner, the economic cost of GHG emissions can be considered directly during the optimization of a design project using a life-cycle analysis combined with values for the cost to society for the pollutants under consideration. This approach has generated considerable controversy and was removed from the EPA website in January 2017.

Self-Assessment Test

Questions

1. What is the difference between a conventional design and a sustainable design?
2. What is a life-cycle analysis, and how can it be used to develop sustainable designs?
3. How does sustainability affect the optimization of a design?

Answers

1. A conventional design is based on maximizing the profits of the design process without regard to the sustainability of the project. A sustainable design project also maximizes profits from the project, but it does so while producing a design that does not compromise the ability of future generations to meet their needs.
2. A life-cycle analysis is a thorough analysis of a process or product with regard to the resources consumed and the pollution generated considering everything from the materials used to the produce the product to the manufacturing process to the end-of-life of the product. It is used in a sustainable design in order to consider all the sources of resource consumption and pollution generated for a particular design.

3. Sustainable designs require a more comprehensive optimization analysis and generally result in more expensive designs compared to conventional designs because conventional designs neglect many factors considered by a sustainable design.

1.5 Ethics

Engineering ethics is a collection of moral principles applied in engineering practice. Put simply, engineering ethics is the rules of fair play that engineers operate under while serving the public, their employer, the client, and the profession. Engineering offers great potential for contributing to the public good, but at the same time, it can cause great harm if it is not applied correctly and ethically.

Around the turn of the twentieth century after the Industrial Revolution, engineers were playing a major role by contributing to manufacturing and the infrastructure for transportation. When structural failures caused by technical errors, construction problems, and ethical issues created major disasters [(e.g., Ashtabula River Railroad Disaster (1876), Tay Bridge Disaster (1879), Quebec Bridge Collapse (1907), and the Boston Molasses Flood (1919)], a number of the engineering societies adopted formal codes of ethics. These codes made it clear that engineers were responsible for protecting the safety of the public. In 1946, the National Society of Professional Engineers released the Canons of Ethics for Engineers and the Rules for Professional Conduct, which have evolved into the code of engineering ethics used today. Engineering ethics has become even more complicated today due to different cultural traditions encountered in global trade and when dealing with political corruption, environmental issues, and sustainability issues.

Arthur C. Little, who was a famous design engineer, once said, “Any sufficiently advanced technology is indistinguishable from magic.” The engineering profession must thus use its magic wisely.

1.5.1 The Engineering Profession

A profession is a paid occupation that requires special education, training, or skills. Professions are known to evolve through a series of stages: the craft stage, the commercial stage, and the professional stage. The craft stage involves individuals who use common sense, intuition, and brute force to accomplish a task (e.g., building a bridge). As the demand for the task increases, the commercial stage develops and uses practitioners who use trial-and-error methods to improve the consistency and quality of the product. When science catches up with practice, the professional stage begins, combining scientific understanding with practice. As a result, professional engineering practitioners must be trained in scientific theory as well as engineering practice.

Significantly important to the engineering profession are professional engineering societies. Each of the major fields of engineering has a national society [(e.g., the American Institute of Chemical Engineers (AIChE)]. In addition, there are other engineering societies, including the Society of Women Engineers (SWE), the American Society for Engineering Education (ASEE), the National Society of Black Engineers (NSBE), Tau Beta Pi Engineering Honor Society (TBP), and the National Society of Professional Engineers (NSPE). Each of these societies represents a group of engineers and affords a means of interacting with other engineers who share similar backgrounds and interests.

The engineering profession is different from other professions, such as medical doctors, dentists, accountants, and lawyers, because these professionals deal largely with individuals, while engineers work primarily with organizations, such as companies or governmental agencies. The state of a profession depends on those professionals who are engaged in its practice. Moreover, the reputation and/or image of a profession can have a direct effect on the members of that profession. The future reputation of the engineering profession will depend on how technically well and ethically you perform your job as an engineer. Therefore, when you become an engineer, you accept the responsibility to improve or at least maintain the reputation of the engineering profession for those who will follow you.

1.5.2 Codes of Ethics

A number of ethics codes have been developed by engineering societies. Put simply, **engineering ethics boils down to being fair and honest while performing your duties for your employer and client but ultimately protecting the interests of the public.** That is, the public health, welfare, and safety supersede the interest of the employer and the client. If you are aware of a public safety issue, you are required by ethics codes to see that it is corrected or that the proper authorities are notified. In addition, engineers should work only on projects for which they have the necessary education or experience. Remember that whenever you sign your name to a document, you are confirming the accuracy and validity of it with your reputation.

The challenge associated with being ethical occurs when taking the right action costs you. For example, imagine if, based on the course syllabus, you earned a grade of C in a course, but you actually received an A in the course due to a clerical error. It is not ethical to ignore the error and keep the A. For another example, consider that you are working as an engineer and for the first time have been asked to lead a project. Therefore, this project is a launching point for your career. After the project was completed and deemed a huge success, you realize that the whole basis of the project violates a patent that your company does not hold. If you point out the patent infringement to your boss, who designed the project in the first place, this can sabotage your career.

A **conflict of interest** can create a problem for an organization even if no wrongdoing occurs. A conflict of interest can be defined as a set of circumstances that creates a risk that a professional judgment or decision may be affected by a secondary interest—for example, if you were a grader for homework in a class and had to grade your best friend in this class. As a result, **any potential conflict of interest should be disclosed to all parties by an engineer, and the parties should be left to decide if the potential conflict of interest is relevant.**

Plagiarism is the use of someone else's words, ideas, or other work (e.g., images, videos, and music) without referencing the original source. While many times plagiarism is not illegal, it is considered unethical in most organizations. Moreover, in universities, plagiarism is considered academic misconduct and can lead to disciplinary action. A number of software products are available to check for plagiarism, and many university professors routinely use them. Therefore, as an engineer, you should always be careful to reference the sources that you use for all work on which you place your name.

The primary portion of the fundamental canons of the code of ethics for the National Society of Professional Engineers (http://www.nspe.org/resources/ethics/code-ethics) follows:

I. Fundamental Canons

Engineers, in the fulfillment of their professional duties, shall:

1. Hold paramount the safety, health, and welfare of the public.
2. Perform services only in areas of their competence.
3. Issue public statements only in an objective and truthful manner.
4. Act for each employer or client as faithful agents or trustees.
5. Avoid deceptive acts.
6. Conduct themselves honorably, responsibly, ethically, and lawfully so as to enhance the honor, reputation, and usefulness of the profession.

Example 1.2 Copy of Exam

Case Description

Consider that you found a copy of the upcoming exam along with the solution in front of your professor's office door. Moreover, assume that you are currently failing this class and that a failing grade will result in your having to leave the university because you are on scholastic probation.

Analysis

While the fact that you are failing the class and on scholastic probation certainly increases the importance of your decision concerning the copy of the exam and solution, it does not impact the ethical issues of this case. The issue with regard to what to do with the exam is that it would not be fair to the other students in the class for you to use it to get a better grade on the exam. Sliding the material under your professor's door without looking at it further is probably the best option because taking it to the department office would likely embarrass your professor.

It is true that it would be quite difficult to do the right thing in this case given the compromised position that you find yourself in. This example makes the point that **it is much easier to make the right and ethical decision if you do not let yourself get into a compromised position.** Moreover, in this case, even if you were to use the exam and solution to pass this exam, you would not be able to stay in school unless you put the proper effort into your remaining classes.

Self-Assessment Test

Questions

1. Summarize what engineering ethics is.
2. What is a conflict of interest? Give an example.

Answers

1. Engineering ethics is being fair and honest while performing your duties to your employer and client, but ultimately protecting the interest of the public. In addition, as an engineer, you should always disclose any conflicts of interest to the affected parties. Moreover, you should only undertake work for which you have the appropriate background and experience to perform.
2. A conflict of interest is a set of circumstance that creates a risk that a professional judgment or decision may be affected by a secondary interest. If you, as a student, were asked to grade your own exam, that would be a conflict of interest.

Summary

- Chemical engineers are primarily process engineers and hold a variety of jobs for a wide range of industries.
- A sustainability analysis of a product or a process involves a wide range of considerations for a chemical engineer. The quantitative analysis of sustainability requires the use of detailed models, and the following chapters present some of the fundamentals used to develop these models.
- Ethics is about being honest and fair to all parties while protecting society. It is important for engineers to always act in an ethical fashion in order to maintain the reputation of the engineering profession for future generations.

Glossary

CAD Computer-aided design packages (software) that perform design calculation.

CPI The chemical process industries (e.g., refineries and chemical plants).

green engineering Design based on minimizing the total impact of the design on the environment and important resources.

life-cycle analysis A thorough approach for evaluating the impact of a design on the environment and important resources.

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