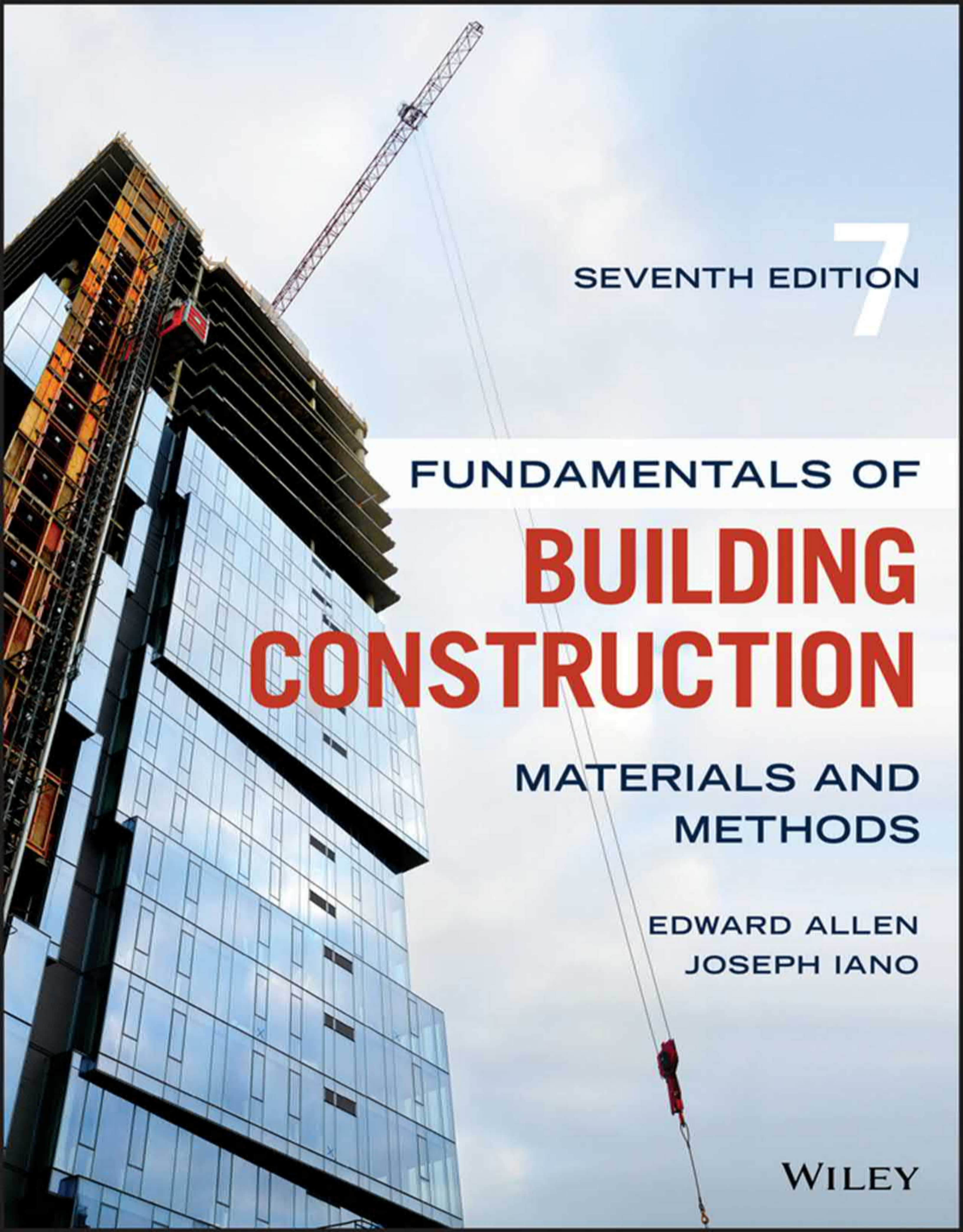

SEVENTH EDITION 7

FUNDAMENTALS OF BUILDING CONSTRUCTION

MATERIALS AND METHODS

EDWARD ALLEN
JOSEPH IANO

WILEY

Fundamentals of Building Construction

Fundamentals of Building Construction

Materials and Methods

Seventh Edition

Edward Allen and Joseph Iano

Wiley

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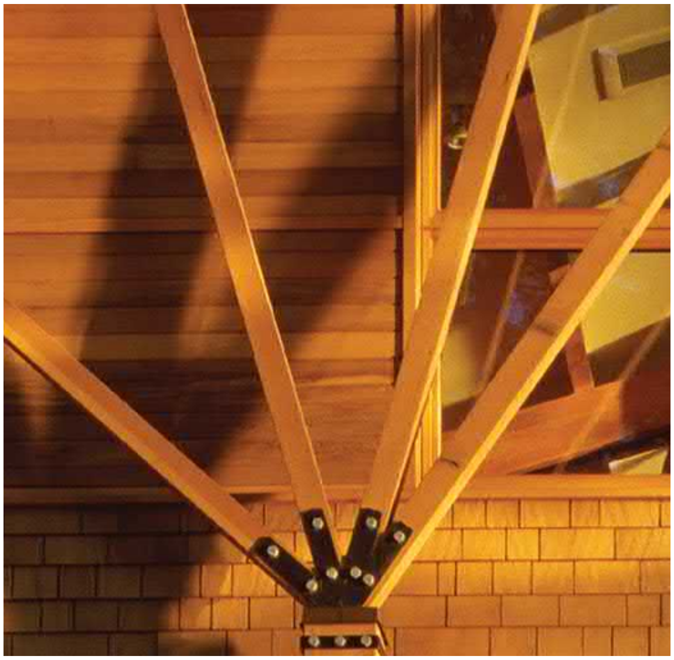

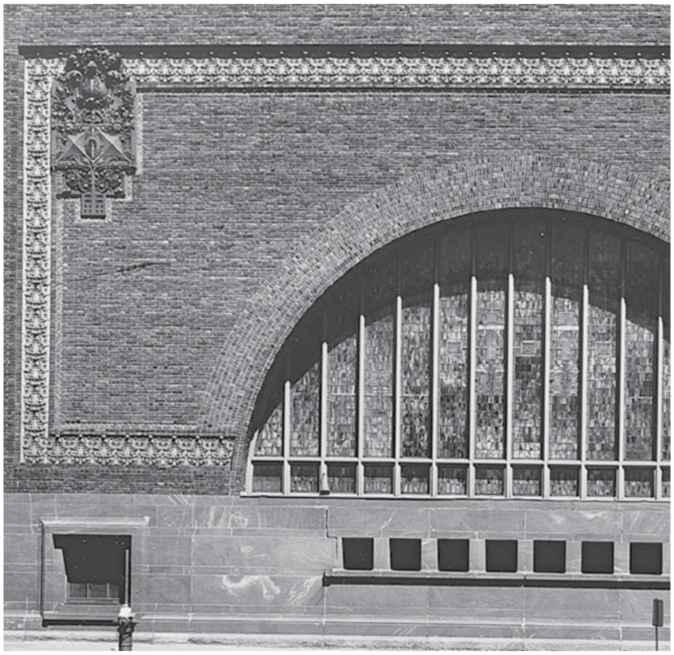

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Preface to the *Seventh Edition*

First published over a quarter century ago, *Fundamentals of Building Construction: Materials and Methods* has wrought a revolution in building construction education. It made a previously unpopular area of study not merely palatable but vibrant and well liked. It has taken a practical, and at times undervalued, body of knowledge and made it widely recognized as centrally relevant to good building design. It has replaced dry, unattractive books with a well-designed, readable volume that students value and keep as a reference work. It was the first book in its field to be evenhanded in its coverage and profusely and effectively illustrated throughout. It was the first to release the teacher from the burden of explaining everything in the subject, thereby freeing class time for discussions, case studies, field trips, and other enrichments.

Gaining a useful knowledge of the materials and methods of building construction is crucial and a necessity for the student of architecture, engineering, or construction, but it can be a daunting task. The field is broad, diverse, complex, and under constant change, such that it seems impossible to ever master. This book has gained its preeminent status as an academic text in this field because of its logical organization, outstanding illustrations, clear writing, and distinctive philosophy.

It is *integrative*, presenting a unified narrative that interweaves issues of building science, material properties, building craft, and legal constraints so that the reader does not have to refer to separate parts of the book to make the connections among these issues. The elements of building construction are presented as whole working systems rather than disconnected parts.

It is *selective* rather than comprehensive. This makes it easy and pleasant for the reader to gain a working knowledge that can later be expanded, without piling on so many facts and figures that the reader becomes discouraged from learning about construction. This book deals, as its subtitle indicates, with fundamentals.

It is *empowering* because it is structured around the process of designing and constructing buildings. The student of architecture will find that it features the design possibilities of the various materials and systems. Students interested in building or managing the construction process will find its organization around construction sequences to be invaluable.

This seventh edition incorporates extensive updates and revisions. Chapter 4, now entitled “Heavy Timber and Mass Timber Construction,” covers new and exciting developments in the design and construction of tall wood buildings. We discuss mass timber construction methods, upcoming building code provisions that will regulate this new construction type, and more. A rewritten chapter, now titled “Designing the Building Enclosure,” comprehensively addresses in one place all aspects of building enclosure (“building envelope”) science, making this important material easier for students to access and instructors to teach. In Chapter 1, our coverage of sustainable building has kept pace with this evolving topic, including, for example, an expanded discussion of the increasingly sophisticated tools available for assessing the environmental and health impacts of building materials. Throughout the remainder of the text the reader will find extensive updates in content, along with new illustrations and photographs, reflecting the latest practices and developments in the field.

In this edition, a special thank-you goes to Fast + Epp engineers, and in particular, Davin Lewis, P.E., of that firm, for their generous advice and assistance. Thank you as well to David Barber of Arup and Colin Shane of RDH for their efforts. Lastly, we offer our thanks to the many teachers, students, and professionals who have purchased and used this work. Your satisfaction is our greatest reward, your loyalty is greatly appreciated, and your comments are always welcome!

—E.A., Weyland, Massachusetts
—J.I., Seattle, Washington

Additional resources for instructors and students are readily available via the companion website: www.wiley.com/go/allenfbc7e.

Icons throughout the text indicate SketchUp exercises and animations which are also available for download on the companion website.

Fundamentals of Building Construction

1

Making Buildings

An ironworker connects a steel wide-flange beam to a column.
(Courtesy of Bethlehem Steel Company.)

We build to satisfy our practical and spiritual needs. Not all human activity can take place outdoors. We need shelter from sun, wind, rain, and snow. We need dry, level surfaces for our activities. On these sheltered surfaces, we need air that is warmer or cooler, more or less humid, than outdoors. We need less light by day, and more by night, than is offered by the natural world. We need services that provide energy, communications, water, and disposal of wastes. And we need structures that house and express our cultural and spiritual aspirations. So, we gather materials and assemble them into the constructions we call buildings in an attempt to satisfy these needs.

Learning to Build

This book is about the materials and methods of building construction. Throughout it, alternative ways of building are described: different structural systems, different methods of building enclosure, and different interior finishes, each with characteristics that distinguish it from the alternatives. Sometimes a choice between alternatives is based on visual characteristics, such as when a particular finish material is preferred for its surface character and beauty, or when a material such as concrete is selected over steel for its massiveness and plasticity. Sometimes choices are purely technical, such as the selection of a membrane that is impervious to water for a low-slope roof, or when a particular method of masonry wall reinforcing is selected to provide resistance to earthquake forces. Choices of materials and building systems may be made with the goal of minimizing environmental impacts or they may be dictated by regulations intended to protect public safety and welfare. Construction costs, energy efficiency, durability, and many other factors come into consideration.

This textbook will start you down the path of becoming skilled at making such choices. But it is incumbent upon the student to go beyond what is provided here—to other books, product literature, trade publications, professional periodicals, websites, and especially the design office, workshop, and building site. One must learn how materials feel in the hand; how they look in a building; how they are manufactured, worked, and put in place; how they perform in service; how they age with time. One must become familiar with the people and organizations that produce buildings—the architects, engineers, product manufacturers, materials suppliers, contractors, subcontractors, workers, inspectors, managers, and building owners—and learn to understand their respective methods, problems, and points of view. There is no other way to gain the breadth of information and experience necessary than to get involved in the art and practice of building.

In the meantime, this long and hopefully enjoyable process of education in the materials and methods of building construction can begin with the information presented within this text.

> **Go into the field where you can see the machines and methods at work that make the modern buildings, or stay in construction direct and simple until you can work naturally into building-design from the nature of construction.**
>
> **—Frank Lloyd Wright, "To the Young Man in Architecture," 1931**

Buildings and the Environment

In constructing and occupying buildings, we expend large quantities of the earth's resources and generate a significant portion of its environmental pollution. The construction and operation of buildings account for as much as a third of the world's energy consumption and carbon dioxide (a global warming gas) emissions. In the United States, building operation and construction consume between a third and a half of the country's energy, 70 percent of its electricity, 12 percent of its potable water, 30 percent of its raw materials, and a third of its solid waste. And these same activities are responsible for as much as 45 percent of the country's carbon dioxide emissions. Buildings are also significant emitters of particulates and other air pollutants. In short, building construction and operation contribute to many forms of environmental degradation and place a significant burden on the earth's resources.

In 1987, the United Nations report "Our Common Future" provided a concise definition of *sustainable development*: building to meet the needs of the present generation without compromising the ability of future generations to meet their own needs. But, by consuming irreplaceable fossil fuels and other nonrenewable resources, by building in sprawling patterns on prime agricultural land, by using destructive land development and forestry practices that degrade natural ecosystems, by generating substances that pollute water, soil, and air, and by generating copious amounts of waste materials that are eventually incinerated or buried in the earth, we have been building in a manner that will make it increasingly difficult for our children and their children to meet their needs for communities, buildings, and healthy lives. Sustainable building construction demands a more symbiotic relationship between people, buildings, communities, and

FIGURE 1.1
The Bullitt Center, Seattle, designed by architect Miller Hull Partnership, was the first commercial building to achieve Living Building certification in 2015. This building generates as much as 60 percent more electricity than it uses and consumes less than one-quarter of the energy of a typical U.S. office building. *(Photo by Joe Iano.)*

the natural environment. Sustainable buildings—in both their construction and operation—must use less energy, consume fewer resources, cause less pollution of the air, water, and soil, reduce waste, discourage wasteful land development practices, and contribute to the protection of natural environments and ecosystems.

Over the decades since the release of "Our Common Future," the practice of sustainable design and construction, also called *green building*, has grown. The understanding of the interplay between buildings and the environment has deepened, and standards for assessing the sustainability of materials and construction practices have grown in number and matured in approach. The definition of sustainability has expanded to address the human health impacts of buildings and to include issues of social and economic fairness. And the expectations for the performance of sustainable buildings have, in some cases, moved from doing less environmental harm to doing no harm or even undoing previous such harms. That is, a sustainable building can be designed to consume no energy or even generate excess energy, cause no air pollution or even help clean the atmosphere, and so on (Figure 1.1).

Also during this time, interest in and adoption of green building has broadened among public agencies, private owners, and the users of buildings. The design and construction industry has become more skillful at applying green practices, and sustainable building has become more integrated with mainstream practice. As a result, sustainable building performance continues to improve while the premium in cost and effort to design and construct such buildings continues to decline.

Sustainable Buildings

Sustainable building requires a holistic, interdisciplinary approach to design and construction. For example, one project goal may be to provide natural daylighting, as a means to improving productivity and the well-being of building occupants. Good daylighting design reduces reliance on electric lighting. This, in turn, reduces electricity consumption and excess heat generated by the electric lights. This, then, reduces cooling loads and allows the building's cooling system to be reduced in capacity and physical size. Daylighting design can also influence building siting and shape, the arrangement and sizes of spaces within the building, and the building structure and enclosure. As a result of the decision to provide natural daylighting, many building systems are impacted, and many opportunities for cost savings, reductions in energy consumption, improvements in occupant health and comfort, and lessening of environmental impacts are created.

This kind of design thinking, called *integrated design process* (*IDP*), is a whole-systems way of working that breaks down traditional boundaries between disciplines and parts of the work. All key members of the design, construction, and owner groups are brought together. A clear vision and goals are established. The process spans from the earliest conceptual phase through design, construction, and post-occupancy (the operational phase once the project is completed). And a collaborative, interdisciplinary

LEED for New Construction and Major Renovation

Project Checklist

Project Name

Date

Y	?	N			
			Credit 1	Integrative Process	1
			Location and Transportation	**Possible Points:**	**16**
			Credit 1	LEED for Neighborhood Development Location	16
			Credit 2	Sensitive Land Protection	1
			Credit 3	High Priority Site	2
			Credit 4	Surrounding Density and Diverse Uses	5
			Credit 5	Access to Quality Transit	5
			Credit 6	Bicycle Facilities	1
			Credit 7	Reduced Parking Footprint	1
			Credit 8	Green Vehicles	1
			Sustainable Sites	**Possible Points:**	**10**
Y			Prereq 1	Construction Activity Pollution Prevention	Required
			Credit 1	Site Assessment	1
			Credit 2	Site Development—Protect or Restore Habitat	2
			Credit 3	Open Space	1
			Credit 4	Rainwater Management	3
			Credit 5	Heat Island Reduction	2
			Credit 6	Light Pollution Reduction	1
			Water Efficiency	**Possible Points:**	**11**
Y			Prereq 1	Outdoor Water Use Reduction	Required
Y			Prereq 2	Indoor Water Use Reduction	Required
Y			Prereq 3	Building-Level Water Metering	Required
			Credit 1	Outdoor Water Use Reduction	2
			Credit 2	Indoor Water Use Reduction	6
			Credit 3	Cooling Tower Water Use	2
			Credit 4	Water Metering	1
			Energy and Atmosphere	**Possible Points:**	**33**
Y			Prereq 1	Fundamental Commissioning and Verification	Required
Y			Prereq 2	Minimum Energy Performance	Required
Y			Prereq 3	Building-Level Energy Metering	Required
Y			Prereq 4	Fundamental Refrigerant Management	Required
			Credit 1	Enhanced Commissioning	6
			Credit 2	Optimize Energy Performance	18
			Credit 3	Advanced Energy Metering	1
			Credit 4	Demand Response	2
			Credit 5	Renewable Energy Production	3
			Credit 6	Enhanced Refrigerant Management	1
			Credit 7	Green Power and Carbon Offsets	2

			Materials and Resources		Possible Points: 13
Y			Prereq 1	Storage and Collection of Recyclables	Required
Y			Prereq 2	Construction and Demolition Waste Management Planning	Required
			Credit 1	Building Life-Cycle Impact Reduction	5
			Credit 2	Building Product Disclosure and Optimization — Environmental Product Declarations	2
			Credit 3	Building Product Disclosure and Optimization — Sourcing of Raw Materials	2
			Credit 4	Building Product Disclosure and Optimization — Material Ingredients	2
			Credit 5	Construction and Demolition Waste Management	2
			Indoor Environmental Quality		Possible Points: 16
Y			Prereq 1	Minimum Indoor Air Quality Performance	Required
Y			Prereq 2	Environmental Tobacco Smoke Control	Required
			Credit 1	Enhanced Indoor Air Quality Strategies	2
			Credit 2	Low-Emitting Interiors	3
			Credit 3	Construction Indoor Air Quality Management Plan	1
			Credit 4	Indoor Air Quality Assessment	2
			Credit 5	Thermal Comfort	1
			Credit 6	Interior Lighting	2
			Credit 7	Daylight	3
			Credit 8	Quality Views	1
			Credit 9	Acoustic Performance	1
			Innovation		Possible Points: 6
			Credit 1	Innovation	5
			Credit 2	LEED Accredited Professional	1
			Regional Priority		Possible Points: 4
			Credit 1	Regional Priority: Specific Credit	1
			Credit 2	Regional Priority: Specific Credit	1
			Credit 3	Regional Priority: Specific Credit	1
			Credit 4	Regional Priority: Specific Credit	1
			Total		Possible Points: 110

Certified 40 to 49 points Silver 50 to 59 points Gold 60 to 79 points Platinum 80 to 110

FIGURE 1.2
The LEED v4 New Construction and Major Renovation Project Checklist. *(Courtesy of U.S. Green Building Council.)*

approach is used that maximizes opportunities for synergies and innovation.

In the United States, the most widely applied program for building sustainability is the U.S. Green Building Council's *Leadership in Energy and Environmental Design*, or *LEED*®, rating system. LEED for New Construction and Major Renovation groups sustainability goals into eight broad categories addressing areas such as site selection and development, energy efficiency, conservation of materials and resources, and others (Figure 1.2). Within each category are mandatory *prerequisites* and optional *credits* that contribute points toward a building's overall rating. During the design and construction process, the achievement of prerequisites and credits is documented and submitted to the Green Building Council, which then makes the certification of the project's LEED compliance after construction is completed. Depending on the point total achieved, four levels of sustainable performance are recognized, including, in order of increasing performance, Certified, Silver, Gold, and Platinum. The LEED rating system is itself voluntary. It is used when adopted by a private building owner or mandated by a public building agency.

The Green Building Council also provides rating systems for existing buildings, commercial interior buildouts, building core and shell construction, schools, retail buildings, healthcare facilities, homes, neighborhood developments, building operations and maintenance, and other project types. Through affiliated organizations, LEED is also implemented in Canada and other countries.

The International Living Future Institute's *Living Building Challenge*™ sets a higher standard for sustainable building. This program aspires to move past making buildings that do less environmental harm to those that do no harm or even improve the natural environment and our well-being. For example, a building constructed and operated to this standard will (when considered on an annualized basis) generate all its own energy from on-site renewable resources, consume no fresh water, and have no greenhouse gas emissions.

The Living Building Challenge contains seven categories, called Petals, including Place, Water, Energy, Health & Happiness, Materials, Equity, and Beauty. Within these are 20 *Imperatives*, such as net zero energy, appropriate sourcing of materials, embodied carbon footprint, and more. There are three certification levels: Living Building Certification meets all imperatives appropriate to the building type, Petal Certification signifies a lower level of partial compliance, and Zero Energy Certification applies to projects that generate all energy on site without reliance on combustion processes. Certification occurs after a building has been operational for at least one year, when its real-world performance can be assessed. The Living Building Challenge can also be applied to other types of construction and development, such as neighborhoods, landscape and infrastructure projects, and building renovations.

Sustainable Building Materials

Describing Sustainable Materials

Designing sustainable buildings requires access to information about the environmental and health impacts of the materials used in their construction. For example, when selecting a material, the designer might ask: Does its manufacture depend on the extraction of nonrenewable resources, or is it made from recycled or rapidly renewable materials? Is additional energy required to ship this material from a distant location, or can it be obtained from local sources? Does the material contain toxic ingredients or generate unhealthful emissions, or is it free of such health concerns?

Information about building materials and products can come from different sources and take various forms:

- It may be self-reported by the product manufacturer, or it may come from an independent, trusted third party.
- It may take the form of a neutrally expressed, transparent disclosure of material attributes, or it may gauge the merits (or demerits) of such attributes and provide a rating of the material's sustainability.
- It may address a limited scope of concerns, or it may describe the full range of impacts of a material throughout its life cycle from raw materials extraction to end-of-life disposal or repurposing.

The industry-standard *Product Data Sheet* (*PDS*) is a simple example of manufacturer self-reported information. The PDS provides a description of a product, its material makeup and physical properties, and guidelines for use. It may also include information relevant to sustainability concerns, although this is not its primary purpose. The scope of information provided in a PDS is left entirely to the manufacturer, and the information is not independently verified.

Other Sustainable Building Programs and Standards

There are many programs and standards offering alternative pathways to sustainable building construction, suitable to various building types, objectives, and construction markets. For example, the U.S. National Association of Home Builders' National Green Building Standard addresses both single-family and multi-unit residential building types. The International Green Construction Code is a model code that puts green building standards into a legally enforceable format that is useful for municipalities that wish to mandate sustainable construction. CALGreen is the sustainable construction code for the state of California. Green Globes certifies new and existing sustainably designed buildings in the United States and Canada. The Building Research Establishment Environmental Assessment Method, or BREEAM, does the same for buildings constructed in the United Kingdom and other European countries. The Passive House Standard, implemented in many places around the globe, emphasizes dramatic reductions in the energy consumption of residential and commercial buildings. The International WELL Building Institute's WELL Building Standard certifies building construction with regard to human health and well-being criteria. In addition, professional organizations and government agencies offer programs to support sustainable building, such as the Architecture 2030 Challenge and ASHRAE's Standard for the Design of High-Performance Green Buildings, to name just two.

Environmental labels, also called *ecolabels*, are third-party environmental ratings. An example is the Green Seal Standard GS-11 for Paints and Coatings. Green Seal is an independent organization that develops sustainability standards and certifications. For a paint product to be certified to its standard, the product must meet minimum performance criteria, be free of toxic ingredients, and not exceed content limits on *volatile organic compounds* (*VOCs*). (VOCs are air polluting and unhealthful chemical compounds that are released in particularly heavy concentrations from wet-applied products as they dry.) By relying on this certification, the designer can confidently make environmentally responsible choices, without having to perform in-depth investigations of individual products.

Product disclosures are another form of reporting that provide transparent information about material ingredients and manufacturer practices. For example, the International Living Future Institute's Declare label describes a product's origins, its material ingredients, and end-of-life disposal or recycling options. By providing this information in a standardized format, designers can more easily compare the relative attributes of alternative materials or products and make better-informed choices. Like a Product Data Sheet, the Declare label is self-reported by manufacturers, albeit with an option for independent auditing to verify accuracy. Unlike ecolabels, product disclosures do not rate the sustainability of the product—it remains up to the user to interpret the information provided for this purpose.

Environmental Product Declarations (*EPDs*) describe the full, life-cycle environmental impacts of building materials and products. An example is the Western Red Cedar Lumber Association's Typical Red Cedar Decking Product Declaration. This 10-page document describes this product's material characteristics and quantifies—in some detail—environmental impacts throughout its life. For example, for every 1 square meter (11 square feet) of decking harvested, milled, trucked to the construction site, installed, maintained through its useful life, and then disposed of at the end of its life, this declaration reports the following:

- 73 MJ (70,000 BTU) of nonrenewable energy consumed
- 6.8 kg (15 pounds) of CO_2 equivalent *global warming potential*
- 86 L (23 gallons) of fresh water consumed

Additional information in the report quantifies materials consumption, smog production, ozone depletion, acidification and eutrophication potential, waste materials generated, and more. Information about the standards to which this information is prepared and independent verification of the results are also included. While this document does not provide an environmental rating, it can be used, for example, in comparing Western red cedar to some other material, such as recycled plastic decking, to assess the relative environmental consequences of choosing one of these materials over the other.

In relative infancy are *Environmental Building Declarations*, or *EBD*s. As life-cycle data become available for the majority of materials and products used in construction, the same type of life-cycle analysis can be applied to whole buildings, allowing the environmental impacts of alternative building designs to be meaningfully compared.

Much of the environmental reporting provided by product manufacturers is developed according to the international series of standards designated *ISO 14020*, which establish guidelines for the development and use of environmental labels and declarations. By relying on information produced to common, accepted standards, designers and builders can have the greatest confidence in the consistency and relevance of the information provided.

The Material Life Cycle and Embodied Impacts

Preparation of environmental product and building declarations depends on the accounting of the environmental impacts of materials and products throughout their life cycles. This begins with raw materials extraction, continues with manufacture, construction, and use, and finishes at end of life when a material is disposed of or put to a new use. Such a *life-cycle analysis* (*LCA*), or *cradle-to-grave analysis*, is one of the most comprehensive methods for quantifying the environmental impacts associated with materials and buildings. Through each life-cycle stage, impacts are tallied: How much fossil fuel, electricity, water, and other materials are consumed? How much solid waste, global warming gasses, and other air and water pollutants are generated? The total of all these impacts describes the *environmental footprint* of the material (Figure 1.3).

The concept of embodied energy also derives from life-cycle analysis. *Embodied energy* is the sum total of energy consumed during a material's life cycle. Because energy consumption frequently correlates with the consumption of nonrenewable resources and the generation of greenhouse gasses, it is easy to assume that materials with lower embodied energy are better for the environment than others with greater embodied energy. However, in making such comparisons, it is important to be sure that the comparison is functionally equivalent. For example, a material with an embodied energy of 10,000 BTU per pound is not necessarily environmentally preferable to another with an embodied energy of 15,000 BTU per pound, if 2 pounds of the prior material are required to accomplish the same purpose as 1 pound of the latter. The types of energy consumed for each material, such as fossil, nuclear, or renewable,