

MECHANICAL AND ELECTRICAL EQUIPMENT

ELEVENTH EDITION



FOR BUILDINGS

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Mechanical
and Electrical
Equipment
for Buildings

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Preface

SEVEN DECADES AND A FEW GENERATIONS have passed since the first edition of *Mechanical and Electrical Equipment for Buildings* was published in 1935. At its birth, this book was 429 pages long. Now, in the 11th edition, the book is more than 1700 pages, an increase of 400%. Many new topics have been added, and a few have disappeared; computer simulations are now routinely used in system design; equipment and distribution systems have undergone major changes; mechanical cooling has become commonplace; fuel choices have shifted (coal has moved from an on-site to an off-site energy source). In recent editions, the book has increasingly added discussions of “why” to its historic focus upon “how-tos.”

Most of the systems presented in this book involve energy consumption. As North American society has moved from its early reliance on renewable energy sources (wind, water, and horse power) to today’s seemingly endless addiction to nonrenewable fossil fuels, it has also added vastly to its population and increased its per capita energy use. The resulting environmental degradation (primarily evident in air and water quality) has spurred efforts to reverse this decline. Governmental regulations are a part of such efforts, but this book emphasizes the investigation of alternative fuels and design approaches that go beyond those minimally acceptable to society. Designers are encouraged to take a leadership role in mitigating environmental degradations.

On this note, it is becoming increasingly clear that global warming is well under way. It may be less clear to what precise extent our hugely increased carbon-based energy consumption is responsible, with its associated heat release and gaseous additions to the atmosphere. But it is very clear that the world’s supply of fossil fuel is diminishing, with future consequences for all buildings (and their occupants) that today rely so thoroughly on nonrenewable energy sources.

The buildings of today contribute to negative global consequences that will impact future generations, and our approach to mechanical and electrical systems must consider how best to minimize and mitigate—if not negate—such negative environmental impacts. Thus, on-site resources—daylighting, passive solar heating, passive cooling, solar water heating, rainwater, wastewater treatment, photovoltaic electricity—share the spotlight with traditional off-site resources (natural gas, oil, the electrical grid, water and sewer lines). On-site processes can be area-intensive and labor-intensive and can involve increased first costs that require years to recover through savings in energy, water, and/or material consumption. Off-site processes are usually subsidized by society, often with substantial environmental costs. On-site energy use requires us to look beyond the building, to pay as much attention to a building’s context as to the mechanical and electrical spaces, equipment, and systems within.

Throughout the many editions of this book, another trend has emerged. Society has slowly moved from systems that centralize the provision of heating, cooling, water, and electricity toward those that encourage more localized production and control. Increased sophistication of digital control systems has encouraged this trend. Further encouragement comes from multipurpose buildings whose schedules of occupancy are fragmented and from corporations with varying work schedules that result in partial occupancy on weekends. Another factor in this move to decentralization is worker satisfaction; there is increasingly solid evidence that productivity increases with a sense of individual control of one’s work environment. Residences are commonly being used as office work environments. Expanding communications networks have made this possible. As residential designs thus become more complex (with office-quality lighting, zones

for heating/cooling, sophisticated communications, noise control), our nonresidential work environments become more attractive and individual.

Air and water pollution problems stemming from buildings (and their systems and occupants) are widely recognized and generally condemned. A rapidly increasing interest in green design on the part of clients and designers may help to mitigate such problems, although green design is hopefully just an intermediate step in the journey to truly sustainable solutions.

Another pervasive pollutant affecting our quality of life is noise. Noise impacts building siting, space planning, exterior and interior material selections—even the choice of cooling systems (as with natural ventilation). Air and water pollution can result in physical illness, but so can noise pollution, along with its burden of mental stress.

This book is written primarily for the North American building design community and has always emphasized examples from this region. Yet other areas of the world, some with similar traditions and fuel sources, have worthy examples of new strategies for building design utilizing on-site energy and energy conservation. Thus, some buildings from Europe and Asia appear in this 11th edition, along with many North American examples. Listings of such buildings (and associated researchers and designers) have been included in the index of this edition.

Building system design is now widely undertaken using computers, often through proprietary software that includes hundreds of built-in assumptions. This book encourages the designer to take a rational approach to system design: to verify intuitive design moves and assumptions and to use computers as tools to facilitate such verification, but to use patterns and approximations to point early design efforts in the right direction. Hand calculations have the added benefit of exposing all pertinent variables and assumptions to the designer. This in itself is a valuable rationale for conducting some portion of an analysis manually. Rough

hand-calculated results should point in the same direction as results obtained with a computer; the greater the disparity, the greater the need to check both approaches. This is not to disparage the use of simulations, which are valuable (if not indispensable) in optimizing complex and sometimes counterintuitive systems.

This book is written with the student, the architect- or engineer-in-training, and the practicing professional in mind. Basic theory, preliminary design guidelines, and detailed design procedures allow the book to serve both as an introductory text for the student and as a more advanced reference for both professional and student. This work is intended to be used as a textbook for a range of courses in architecture, architectural engineering, and building/construction management.

A “MEEB 11” World Wide Web (WWW) site will provide supporting materials to enhance learning about and understanding the concepts, equipment, and systems dealt with in this book. The opportunity to provide color images via this medium is truly exciting. As with previous editions, an Instructor’s Manual has been developed to provide additional support for this 11th edition. The manual, prepared by Kristen DiStefano, Walter Grondzik and Alison Kwok, outlines the contents and terminology in each chapter; highlights concepts of special interest or difficulty; and provides sample discussion, quiz, and exam questions. The manual is available to instructors who have adopted this book for their courses.

Mechanical and Electrical Equipment for Buildings continues to serve as a reference for architectural registration examinees in the United States and Canada. We also hope to have provided a useful reference book for the offices of architects, engineers, construction managers, and other building professionals.

WALTER T. GRONZIK
ALISON G. KWOK
BENJAMIN STEIN
JOHN S. REYNOLDS

Visit **www.wiley.com/go/meeb**
for the expanding set of learning resources that accompany this book.

Acknowledgments

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In addition to drawings by Michael Cockram (whose work first appeared in the 8th edition), we are very pleased to include in this 11th edition illustrations by Lisa Leal, Nathan Majeski, and Jonathan Meendering (who also helped illustrate the 10th edition). We continue to thank those who assisted with illustrations for the 10th edition: Dain Carlson, Amanda Jo Clegg, Eric Drew, and Erik Winter—students (now professionals) who embrace the principles and concepts of environmental technology in their design work and therefore clearly understood what they were drawing. We also acknowledge the many architects and engineers who provided illustrations of their buildings and design artifacts that

appear throughout the book—citations to these firms and individuals are found throughout the book.

Testing in the classroom is a particularly valuable way to find needed improvements in any textbook. Students at the University of Oregon have, over many years, raised probing questions whose answers have resulted in changes to succeeding editions. Valuable suggestions have come from many graduate teaching fellows at the University of Oregon, particularly Rachel Auerbach, Christina Bollo, Alfredo Fernandez-Gonzalez, Sara Goenner, Jeff Guggenheim, Susie Harriman, Jake Keeler, Angela Matt, Jonathan Meendering, Tobin Newburgh, Roger Ota, Therese Peffer, Troy Peters, David Posada, Barbara Reed, Amanda Rhodes, Nick Rajkovich, Jonathan Thwaites, and Michael Walsh. Michael Ober provided unrestrained encouragement with a YouTube video special for “MEEB.” Former Oregon students who helped with research include Troy Anderson, Daniel Irurah, Reza Javandel, Jeff Joslin, and Emily Wright.

A large portion of the work involved in producing a manuscript is accomplished by supporting personnel. Among these, we wish particularly to thank Jackie Kingen for coordinating illustrations for this edition. Britni Jessup, Jocelynn Gebhart, Amanda Rhodes, Lisa Leal, and Rachel Auerbach receive thanks for long hours of assistance with file coordination and project management. Adrienne Leverette—thanks for your surprise visit and assistance. Special, and very sincere, thanks go to Theodore J. Kwok, who gave extensive and prompt input on database development and troubleshooting.

Finally, we are indebted to the staff at John Wiley & Sons for their diligent and highly professional work, especially Amanda Miller, vice president and publisher; Paul Drougas, acquisitions editor; Lauren Olesky, associate developmental editor; Sadie Abuhoff, editorial assistant; Kerstin Nasdeo, production manager; Abby Saul, production assistant; and Devra Kunin at Foxxe Editorial Services, copyeditor.

DESIGN CONTEXT

Often mechanical and electrical equipment for buildings is not considered until many important design decisions have already been made. In too many cases, such equipment is considered to have a corrective function, permitting a building envelope and siting to “work” in a climate that was essentially ignored.



Part I is intended to encourage designers to use the design process to full advantage and to include both climate and the key design objectives of comfort and indoor air quality in their earliest design decisions. Chapter 1 discusses the design process and the roles played by factors such as codes, costs, and verification in shaping a final building design. The critical importance of clear design intents and criteria is emphasized. Principles to guide environmentally responsible design are given. Chapter 2 discusses the relationship of energy, water, and material resources to buildings, from design through demolition. The concept of environmental footprint is introduced as the ultimate arbiter of design decision making. Chapter 3 encourages viewing a building site as a collection of renewable resources, to be used as appropriate in the lighting, heating, and cooling of buildings. Chapter 4 discusses human comfort, the variety of conditions that seem comfortable, and implications of a more broadly defined comfort zone. It includes an introduction to design strategies for lighting, heating, and cooling. Chapter 5 introduces the issue of indoor air quality, which is currently a major concern of building occupants and the legal profession and an underpinning of green design efforts.

Design Process

IN MARCH 1971 VISIONARY ARCHITECT Malcolm Wells published a watershed article in *Progressive Architecture*. It was rather intriguingly and challengingly titled “The Absolutely Constant Incontestably Stable Architectural Value Scale.” In essence, Wells argued that buildings should be *benchmarked* (to use a current term) against the environmentally regenerative capabilities of wilderness (Fig. 1.1). This seemed a radical idea then—and remains so even now, over 30 years later. Such a set of values, however, may be just what is called for as the design professions inevitably move from *energy-efficient* to *green* to *sustainable* design in the coming decades. The main problem with Wells’s “Incontestably Stable” benchmark is that most buildings fare poorly (if not dismally) against the environment-enhancing characteristics of wilderness. But perhaps this is more of a wakeup call than a problem.

As we enter the twenty-first century, *Progressive Architecture* is no longer in business, Malcolm Wells is in semiretirement, mechanical and electrical equipment has improved, simulation techniques have radically advanced, and information exchange has been revolutionized. In broad terms, however, the design process has changed little since the early 1970s. This should not be unexpected, as the design process is simply a structure within which to develop a solution

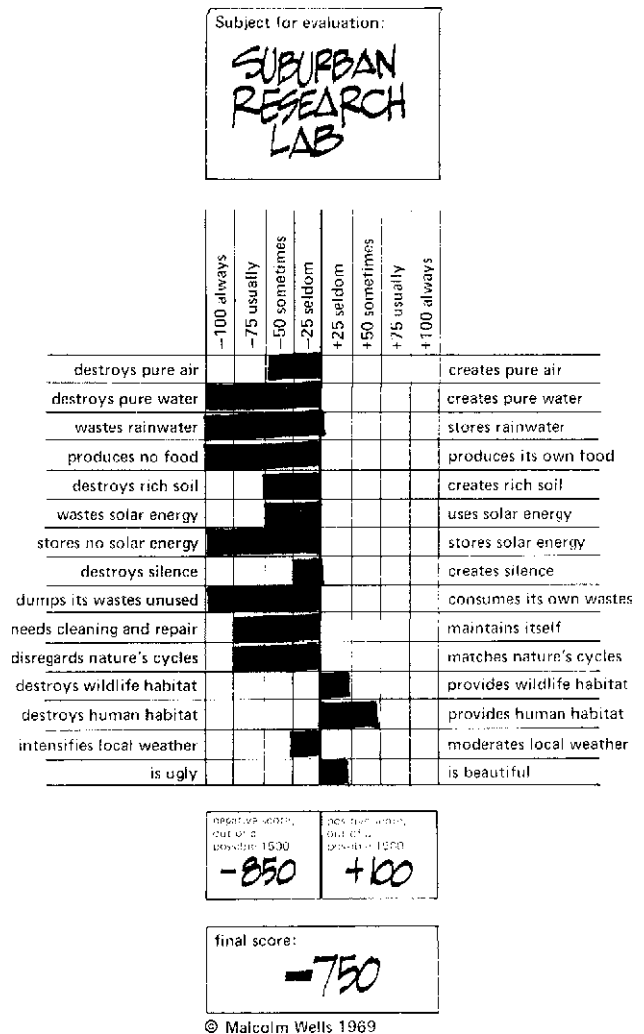


Fig. 1.1 Evaluation of a typical project using Malcolm Wells’s “absolutely constant incontestably stable architectural value scale.” The value focus was wilderness; today it might well be sustainability. (© Malcolm Wells. Used with permission from Malcolm Wells. 1981. *Gentle Architecture*. McGraw-Hill. New York.)

to a problem. The values and philosophy that underlie the design process absolutely must change in the coming decades. The beauty of Wells's value scale was its crystal-clear focus upon the values that accompanied his design solutions—and the explicit stating of those values. To meet the challenges of the coming decades, it is critical that designers consider and adopt values appropriate to the nature of the problems being confronted—both at the individual project scale and globally. Nothing less makes sense.

1.1 INTRODUCTION

The design process is an integral part of the larger and more complex building procurement process through which an owner defines facility needs, considers architectural possibilities, contracts for design and construction services, and uses the resulting facility. Numerous decisions (literally thousands) made during the design process will determine the need for specific mechanical and electrical systems and equipment, and very often will determine eventual owner and occupant satisfaction. Discussing selected aspects of the design process seems a good way to start this book.

A building project typically begins with pre-design activities that establish the need for, feasibility of, and proposed scope for a facility. If a project is deemed feasible and can be funded, a multiphase design process follows. The design phases are typically described as conceptual design, schematic design, and design development. If a project remains feasible as it progresses, the design process is followed by the construction and occupancy phases of a project. In fast-track approaches (such as design-build), design efforts and construction activities may substantially overlap.

Pre-design activities may be conducted by the design team (often under a separate contract), by the owner, or by a specialized consultant. The product of pre-design activities should be a clearly defined scope of work for the design team to act upon. This product is variously called a *program*, a *project brief*, or the *owner's project requirements*. The design process converts this statement of the owner's requirements into drawings and specifications that permit a contractor to convert the owner's (and designer's) wishes into a physical reality.

The various design phases are the primary arena of concern to the design team. The design

process may span weeks (for a simple building or system) or years (for a large, complex project). The design team may consist of a sole practitioner for a residential project or 100 or more people located in different offices, cities, or even countries for a large project. Decisions made during the design process, especially during the early stages, will affect the project owner and occupants for many years— influencing operating costs, maintenance needs, comfort, enjoyment, and productivity.

The scope of work accomplished during each of the various design phases varies from firm to firm and project to project. In many cases, explicit expectations for the phases are described in professional service contracts between the design team and the owner. A series of images illustrating the development of the Real Goods Solar Living Center (Figs. 1.2 and 1.3) is used to illustrate the various phases of a



Fig. 1.2 The Real Goods Solar Living Center, Hopland, California; exterior view. (Photo © Bruce Haglund; used with permission.)

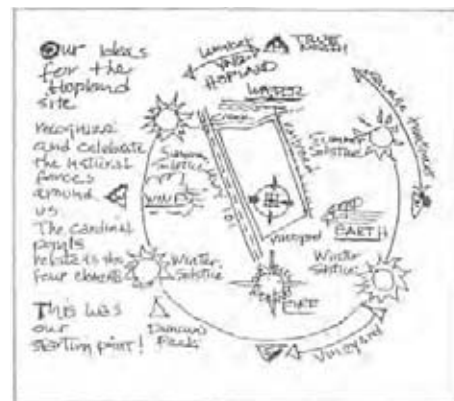


Fig. 1.3 Initial concept sketch for the Real Goods Solar Living Center, a site analysis. (Drawing by Sim Van der Ryn; reprinted from *A Place in the Sun* with permission of Real Goods Trading Corporation.)

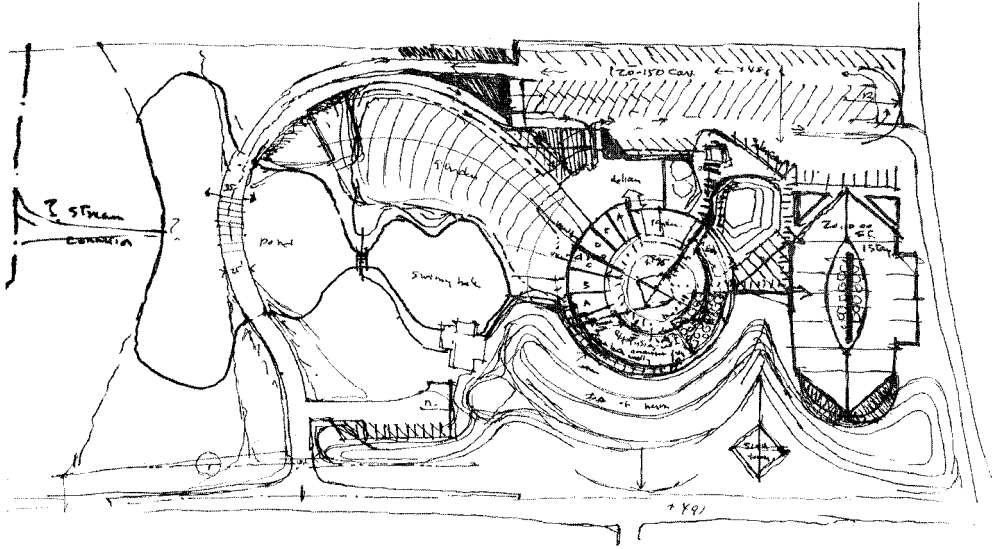


Fig. 1.4 Conceptual design proposal for the Real Goods Solar Living Center. The general direction of design efforts is suggested in fairly strong terms (the “first, best moves”), yet details are left to be developed in later design phases. There is a clear focus on rich site development even at this stage—a focus that was carried throughout the project. (Drawing by Sim Van der Ryn; reprinted from *A Place in the Sun* with permission of Real Goods Trading Corporation.)

building project. (The story of this remarkable project, and its design process, is chronicled in Schaeffer et al., 1997.) Generally, the purpose of conceptual design (Fig. 1.4) is to outline a general solution to the owner’s program that meets the budget and

captures the owner’s imagination so that design can continue. All fundamental decisions about the proposed building should be made during conceptual design (not that things can’t or won’t change). During schematic design (Figs. 1.5 and 1.6), the

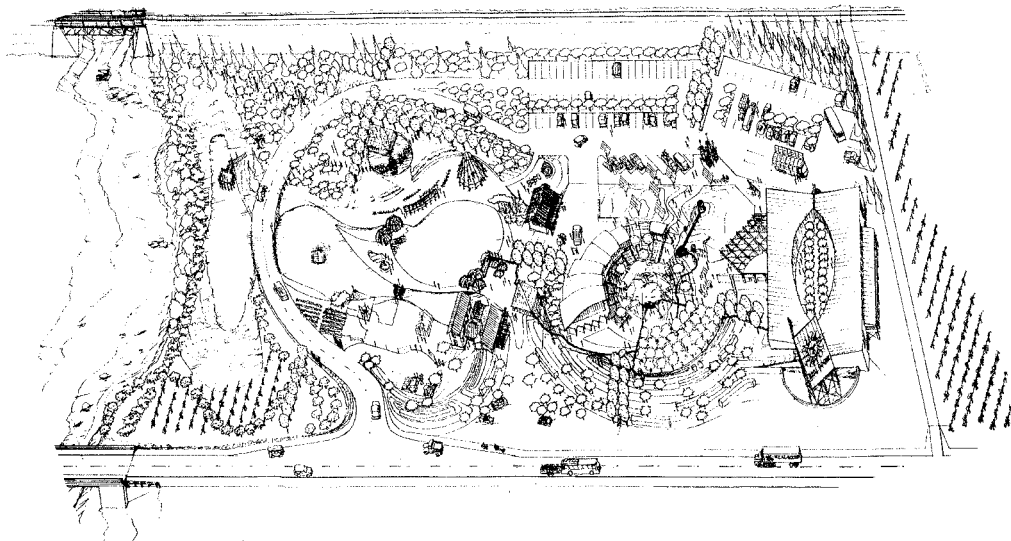


Fig. 1.5 Schematic design proposal for the Real Goods Solar Living Center. As design thinking and analysis evolve, so does the specificity of a proposed design. Compare the level of detail provided at this phase with that shown in Fig. 1.4. Site development has progressed, and the building elements begin to take shape. The essence of the final solution is pretty well locked into place. (Drawing by David Arkin; reprinted from *A Place in the Sun* with permission of Real Goods Trading Corporation.)



Fig. 1.6 Scale model analysis of shading devices for the Real Goods Solar Living Center. This is the sort of detailed analysis that would likely occur during schematic design. (Photo, model, and analysis by Adam Jackaway; reprinted from *A Place in the Sun* with permission of Real Goods Trading Corporation.)

conceptual solution is further developed and refined. During design development (Fig. 1.7), all decisions regarding a design solution are finalized, and construction drawings and specifications detailing those innumerable decisions are prepared.

The construction phase (Fig. 1.8) is primarily in the hands of the contractor, although design decisions determine what will be built and may dramatically affect constructability. The building owner and occupants are the key players during the occupancy phase (Fig. 1.9). Their experiences with the building will clearly be influenced by design decisions and construction quality, as well as by maintenance and operation practices. A feedback loop that allows construction and occupancy experiences (lessons—both good and bad) to be

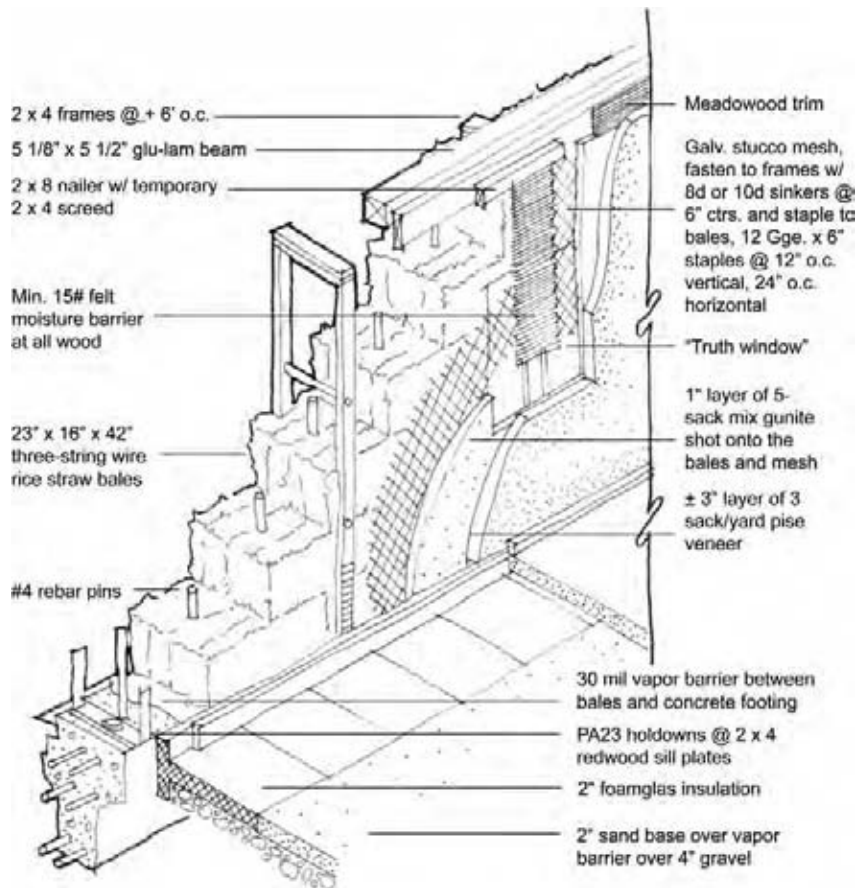


Fig. 1.7 During design development the details that convert an idea into a building evolve. This drawing illustrates the development of working details for the straw bale wall system used in the Real Goods Solar Living Center. Material usage and dimensions are refined and necessary design analyses (thermal, structural, economic) completed. (Original drawing by David Arkin; reprinted from *A Place in the Sun* with permission of Real Goods Trading Corporation. Redrawn by Erik Winter.)



Fig. 1.8 Construction phase photo of Real Goods Solar Living Center straw bale walls. Design intent becomes reality during this phase. (Reprinted from *A Place in the Sun* with permission of Real Goods Trading Corporation.)

used by the design team is essential to good design practice.

1.2 DESIGN INTENT

Design efforts should generally focus upon achieving a solution that will meet the expectations of a well-thought-out and explicitly defined design intent. Design intent is simply a statement that outlines the expected high-level outcomes of the design process. Making such a fundamental statement is critical to the success of a design, as it points to the general direction(s) that the design process must take to achieve success. Design intent should not try to capture the totality of a building's character; this will come only with the completion of the design. It should, however, adequately express the defining



Fig. 1.9 The Real Goods Solar Living Center during its occupancy and operations phase. Formal and informal evaluation of the success of the design solution may (and should) occur. Lessons learned from these evaluations can inform future projects. This photo was taken during a Vital Signs case study training session held at the Solar Living Center. (© Cris Benton, kite aerial photographer and professor, University of California–Berkeley; used with permission.)

characteristics of a proposed building solution. Example design intents (from among thousands of possibilities) might include the following:

- The building will provide outstanding comfort for its occupants.
- The design will consider the latest in information technology.
- The building will be green, with a focus on indoor environmental quality.
- The building will be carbon neutral.
- The building will provide a high degree of flexibility for its occupants.

Clear design intents are important because they set the tone for design efforts, allow all members of the design team to understand what is truly critical to success, provide a general direction for early design efforts, and put key or unusual design concerns on the table. Professor Larry Peterson, former director of the Florida Sustainable Communities Center, has described the earliest decisions in the design process as an attempt to make the “first, best moves.” Strong design intent will inform such moves. Weak intent will result in a weak building. Great moves too late will be futile. The specificity of the design intent will evolve throughout the design process. *Outstanding comfort* during conceptual design may become *outstanding thermal, visual, and acoustic comfort* during schematic design.

1.3 DESIGN CRITERIA

Design criteria are the benchmarks against which success or failure in meeting design intent is measured. In addition to providing a basis against which to evaluate success, design criteria will ensure that all involved parties seriously address the technical and philosophical issues underlying the design intent. Setting design criteria demands the clarification and definition of many intentionally broad terms used in design intent statements. For example, what is really meant by *green*, by *flexibility*, by *comfort*? If such terms cannot be benchmarked, then there is no way for the success of a design to be evaluated—essentially anything goes, and all solutions are potentially equally valid. Fixing design criteria for qualitative issues (such as *exciting*, *relaxing*, or *spacious*) can be especially challenging, but equally

important. Design criteria should be established as early in the design process as possible—certainly no later than the schematic design phase. As design criteria will define success or failure in a specific area of the building design process, they should be realistic and not subject to whimsical change. In many cases, design criteria will be used both to evaluate the success of a design approach or strategy and to evaluate the performance of a system or component in a completed building. Design criteria might include the following:

- Thermal conditions will meet the requirements of ASHRAE Standard 55-2004.
- The power density of the lighting system will be no greater than 0.7 W/ft².
- The building will achieve a Silver *LEED*[®] rating.
- Fifty percent of building water consumption will be provided by rainwater capture.
- Background sound levels in classrooms will not exceed RC 35.

1.4 METHODS AND TOOLS

Methods and tools are the means through which design intent is accomplished. They include design methods and tools, such as a heat loss calculation procedure or a sun angle calculator. They also include the components, equipment, and systems that collectively define a building. It is important that the right method or tool be used for a particular purpose. It is also critical that methods and tools (as means to an end) never be confused with either design intent (a desired end) or design criteria (benchmarks).

For any given design situation there are typically many valid and viable solutions available to the design team. It is important that none of these solutions be overlooked or ruled out due to design process short circuits. Although this may seem unlikely, methods (such as fire sprinklers, electric lighting, and sound absorption) are surprisingly often included as part of a design intent statement. Should this occur, all other possible (and perhaps desirable) solutions are ruled out by direct exclusion. This does not serve a client or occupants well, and is also a disservice to the design team.

This book is a veritable catalog of design guidelines, methods, equipment, and systems that serve