ENERGY MODELING IN ARCHITECTURAL DESIGN

TIMOTHY L. HEMSATH
and KAVEH ALAGHEH BANDHOSSEINI

ROUTLEDGE

Energy Modeling in Architectural Design

Energy Modeling in Architectural Design demonstrates how design elements can lead to energy savings, to help you reduce the energy footprint of your buildings. In addition to identifying climate opportunities, you'll also learn fundamental passive design elements for software-agnostic energy modeling of your projects from conception. Using parametric models and testing each element during design will lead you to create beautiful and high-performance buildings. Illustrated with more than 100 color images, this book also includes a pattern guide for high-performance buildings, discusses energy and daylighting optimization, and has a glossary for easy reference.

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With love to Sawyer and DiAnna

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Foreword

Rives Taylor, FAIA

"How do things get made or built. . . How do they work. . .?"

For many, if not all, designers this lies at the heart of our attraction to the discipline and what got us into this passionate journey of creation and realization in the first place. This passion is what drives the authors to frame this valuable insight into our era's challenging design context. Design performance is the new focal point.

Perhaps now more than at any other time within the history of design do architectural designers, who are the creators of the early twenty-first-century human environment, increasingly carry the mantle of finding balance with the natural environment. In design, we have the imperative to steward the biological environment and the holistic sum of the parts. Our era elevates sustainable design, resilient strategies, resource and human stewardship practices, discussions about global impact of design to mitigate climate shift. These debates have led to calls for integrated process, regenerative, holistic, lifecycle, and net-zero project delivery. This discourse occurs from our design studios through our design practices and is ultimately displayed in the everyday environments we create, build, and operate to support our global wellbeing. Design performance is the new focal point, as Professor Hemsath notes:

> According to the Intergovernmental Panel on Climate Change (IPCC), buildings offer the lowest-cost investment potential for reducing greenhouse gases from carbon emissions. This cost capacity is twice that of any other category, with the second being industry. It helps to know that the decisions we make about a building's design early in the process actually reduce energy consumption and climate emissions—in fact, the IPCC estimates that in the building sector, recent advances in technologies, know-how and policies provide opportunities to stabilize or reduce global energy use to about current levels by mid-century.[1]

However, this is a very tall order: the design disconnect comes in our architectural discipline's seeming inability to connect cause and consequence. Endemic to much of our business thinking perhaps is that architects in the system create products that last for generations. Our profession sees through an awareness of lifecycle thinking, which creates a huge lasting global impact in the construction and operations of that built environment. For over 50 years we have been guilty of profligate energy use, often creating an adversely inhuman, sick building situation. *Energy Modeling in Architectural Design* in its initial overview of the design performance acutely documents our recent history of design and the responses, some with better outcomes than others.

It is the cause-and-effect of architectural design decisions seen in design education, through studio and technology courses at two universities and a global practice; it may be as simple as asking the designer "where is north" with drawings lacking the compass rose. How does the climate affect your design? Is accessibility a driver or simply a code requirement? How are you applying knowledge of wellbeing (much less have you even studied human factors)?

The "mystery of the design process" increasingly is hiding a lack of rigor to recognize design realization or everyday outcomes. Digital design/design virtualization has arisen from our computer-aided design, giving us virtual realization and now virtual reality. Truly incredible forms, designed through a raft of integrated coding processes, allow us to anticipate what a building looks like—but not how it will perform in the environment in a city, much less how the diversity of the human occupants will literally use it or feel about it. Will this virtual environment reflect resource stewardship or human comfort?

One of the many key elements this insightful text offers for the twenty-first-century design process is a clarity of methodology—an integrated design decision process recognizing operational outcomes. This is the best of computational design process—it is a valuable primer of what the design team needs to value in the design and delivery process for energy performance.

Energy simulation modeling, allied with daylight modeling and other resource use mapping, is perceived by too many in the architectural profession as either an academic approach or overtly an engineering-only pursuit, often applied to align the HVAC (heating, ventilation and air conditioning) design with what the architectural team has "thrown over the transom." Many of the tools have evolved to be far friendlier than the early DOE2 versions, as Professor Hemsath notes. The lack of use, or simply using many of these simulation tools just once for the code requirement or LEED prerequisite, comes from the disconnect of the model with the design process and often the disconnect of the modeler from the rest of the team. It is the powerful insight of this text that maps the design teams, their process, and the iterative outcome of an energy simulation to deliver integrated design.

This computational design is increasingly the best practice for client value delivery; we tackle this former design dysfunction/disconnect using a design

inception process called Smart Start, where projected operational and human use performance indicators are documented for continual reference and course correction. This text excels in its documentation of the clear methodology to develop the energy optimization of the owner's project requirements and the attendant integrated architectural and mechanical basis of design. This is not simply for LEED prerequisites, but is the vital tool for the lifecycle for all projects of all scales.

Like so much in the twenty-first century, the evolution of processes, ideas, and global challenges will no doubt make many of our design processes and aesthetics rapidly outdated or out of touch with our client and student demands. Professor Hemsath has delivered more than a toolkit or methodology, but a valuable mindset of performance-based design, couched in a brief but exemplary anthology of our predecessors that influenced architectural design.

Notes

1 Timothy L. Hemsath and Kaveh Alagheh Bandhosseini, *Energy Modeling in Architectural Design* (Routledge, 2018); Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by R.K. Pachauri and L.A. Meyer (Geneva: IPCC, 2014) 102.

Preface

Why in the world am I writing this book? Because I believe that architects must lead building design into our unknown climate future. We achieve leadership through engaging our processes, designing better buildings, and demanding environmental performance. I have been an academic since 2006, when I first began teaching. New to this universe, I found it intimidating yet inspiring. I was previously involved with the U.S. Green Building Council's local chapter in Nebraska and worked briefly at Leo A. Daly.

One big disconnect we observed existed between the architect's wish to design a more sustainable building and the knowledge required to do so. We don't mean to suggest that anyone we've worked with is incompetent, of course, but this point is to identify that often our efforts to do what we think is right for the environment are at odds with our knowledge about what exactly we seek to achieve. An early example is the LEED rating system, plagued by criticism over its point system, which nonetheless moved the building industry toward greater sustainability, by awarding comparable points for often-disparate impacts on the environment. This phenomenon to quantify sustainability continues in other forms; another example is the U.S. Department of Energy-sponsored Solar Decathlon national design/build competition, where the technological value of the houses produced has greater value than their architectural quality. These efforts to measure and count something are important, though they can interfere with our ability to see the true value that design offers our built environment. This book is our attempt to connect the values of architectural design and measurable energy performance to improve the sustainability of our built environment.

Acknowledgments

We wish to acknowledge everyone who made this book possible.

First and foremost is my life partner, best friend, and wife, DiAnna, who helped immensely by covering responsibilities, helping flesh out my grammar for the book, and pushing me to complete this effort, and also our son who has offered love whenever needed.

This book would not have been possible without my coauthor, Kaveh, who put an enormous amount of effort into simulating and writing about his work over our three-plus years working together. We began at zero, learning to understand each other and sharing the ideas that would lead to this production. I published some of our work; the rest is still sitting on my hard drive waiting for me to get to it. I compliment his ambition and persistence to push into the unknown, discover value, and question everything. Wherever he ends up after our adventure, he will surely make an impact as he has in this book.

At the University of Nebraska-Lincoln, I wish to first thank interim deans Kim Wilson and Scott Killinger and Architecture Program Director Jeffrey Day for their monetary support for student workers. I would also have had very little luck pursuing this topic without the passion and efforts of all the students over the years who explored the ideas and tested many of the concepts this book highlights. From seminars to design studios, their work planted the seeds that have grown into this manuscript. Finally, I must specifically thank some of the graduate research assistants and undergraduate workers who spent their summers and semesters working on aspects related to this book: Bryce Willis, Brett Virgl, Adam Weise, and Adam Heier.

My strength is not writing; I relied greatly on Ian Rogers for his editorial expertise in fixing all of my grammatical issues, and appreciate the time he spent revising and suggesting changes to the manuscript. In addition, I owe my ability to rely on his support to our business administrator, Jay Penner, who found some money I had sitting around for Ian's assistance.

I thank the photographers for providing their images and specifically all of the professionals across the U.S. who helped gather the information for the case studies. In alphabetical order:

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Skidmore, Owings & Merrill LLP: Maged Guerguis, Mariana Narvaez, and Emma Bird
Studio Twenty Seven Architecture: Todd Ray and Jim Spearman
Sustainable Engineering Group LLC: Jon Evans

To all my energy-modeling friends, I thank you for letting me bend your ears about this book and what the professional environment needs. Particular thanks to Nathan Kegel at IES for his contributions to energy modeling and my chapter on climate. I've truly enjoyed working with this group of individuals across the world who pursue this frontier of building performance simulation as it relates specifically to energy modeling.

To the academics I have spoken to at other institutions about what they are teaching, how they teach it, and what they use to educate their students with the same values I hold dear. These discussions help inspire me and open my eyes to what great things are happening. There is a lot of work to be done, and it definitely takes all of us, specifically the professionals, to push for carbon neutrality.

I should thank Peter Krebs, the mind behind Sefaira's energy modeling approach, for his brain and for speaking to me about their software plans and efforts, particularly the free educational license they provide all my students every semester to complete the coursework I thrust upon them. I should also thank the DIVA team's Alstan Jakubiec, who has helped us with many simulation issues over the years. He has been open and honest about how DIVA works and assisted in finding solutions and strategies for many of our questions. Finally, Adam Caprez, our connection to the Holland Computing Center at the University of Nebraska-Lincoln.

To conclude, I thank the editorial team at Routledge, and Grace Harrison, who was available to answer my questions. I am also grateful to Wendy Fuller and Norah Hatch for their help leading up to and at the end of the effort finalizing the manuscript.

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Tim is passionate about designing architecture for a sustainable built environment. As an Associate Professor in the College of Architecture, he has over 15 years of combined industry and educational experience in design, construction, and research in energy efficiency and sustainable design. His work includes establishing the Center for Urban Sustainability at the University of Nebraska-Omaha as its founding Research Fellow. He is a member of the Nebraska Community Energy Alliance and past-chair of the Nebraska Flatwater Chapter of the U.S. Green Building Council. He was the design architect for the ZNETH and ZNETH II energy-efficient prototypes working with the College of Engineering at the University of Nebraska-Lincoln, and research PI for the Nebraska Research Initiative-funded project to develop research capacity surrounding zero-net energy research at the University of Nebraska.

Kaveh Alagheh Bandhosseini, PhD
Kaveh Alagheh graduated with a Master of Architecture degree from the Khorasgan branch of Azad University in Iran. After three years of practical experience and having taught in several branches of Azad University, he left Iran to continue his education in architecture. He is a PhD candidate at the University of Nebraska-Lincoln. His extensive work on leveraging digital technologies to improve architectural performance has led to him winning the Per/Form competition, the Beetle[s] plug-in for Grasshopper, and a series of publications in cooperation with Professor Timothy Hemsath.

Rives T. Taylor, FAIA, LEED AP
Principal, Architect—Gensler

A Texas-practicing architect and educator, Rives Taylor, FAIA, LEED AP BD+C, is a Principal and Firmwide Sustainable Design Leader at Gensler, the leading global design firm. He also teaches sustainable design seminars at Rice University and technology curriculum at the UH School of Architecture. Having co-founded the U.S. Green Building Council Houston chapter, the AIA LFRT Green Committee, and engaged in AIA CEU and COTE green, and TxA SusCom efforts, Rives was elevated to his AIA Fellowship for his commitment to sustainable architectural education, mentoring, and practice.

1 Introduction

In an era of climate uncertainty and pressures to reduce carbon emissions, buildings hold the largest share of energy consumption and are therefore a significant contributor of carbon into our atmosphere. We know that buildings consume energy and that conserving energy by operating a building intelligently is important. Since the primary energy source for a building is the power plant, we need to be conscientious in the use of this energy. Carbon limits on coal-fired plants place increased pressure on the use of energy in both new and existing buildings.

According to the Intergovernmental Panel on Climate Change (IPCC), buildings offer the lowest-cost investment potential for reducing greenhouse gases (GHGs) from carbon emissions. This cost capacity is twice that of any other category, with the second being industry. It helps to know that the decisions we make about a building's design early in the process actually reduce energy consumption and climate emissions—in fact, the IPCC estimates that in the building sector, recent advances in technologies, know-how, and policies provide opportunities to stabilize or reduce global energy use to about current levels by mid-century.[1] In the long term, saving energy and reducing GHGs helps save building owners and operators money and prevents wasteful energy use during operation. Energy modeling allows one to demonstrate in measurable terms the energy savings of a building's design from the very conceptualization of a project.

Fundamental decisions made by designers, architects, and engineers early in the design process represent some of the most cost efficient ones. For instance, a building's shape and orientation are decisions made with minimal project cost implications. The building blocks we begin with in design (see Figure 1.1) are essential to conserve energy and use it efficiently. This book puts measurable energy consumption numbers to a few of these design tenets, showing how impactful they are for early design decisions. We can make wiser and more energy-efficient decisions about our building design when considering energy and following a design process that incorporates building energy modeling (BEM) to simulate a building's operational energy use.

There are endless potential building sizes, shapes, and forms—not to mention a wide range of functions and uses—from those with high energy use to low energy use, making it quite a challenge to piece together the range of possibilities. BEM tools employed in architectural design help harmonize them. Using these tools early and often provides the potential to continuously track and benchmark performance against the design goals a team might have for a project. As the building evolves, the specificity of BEM closes in on a more accurate prediction of energy use. A design might start as something simple and evolve into a complex building; using BEM along the way allows us to understand its energy performance from start to finish.

One key to a successful architectural practice today is how to use BEM in the building design process. Using energy modeling is essential to making early fundamental decisions about energy. However, anyone who has attempted to learn the energy modeling process can tell you how overwhelming it can be. There are innumerable barriers to overcome: What software do I use? When should I use it? How does it work? What am I using it for? This book will answer these questions and review in a non-specific software format how to use the tools available, when to use them, and what to do with the outputs to help in the design.

Within the energy modeling field there is an increasing number of BEM professionals certified by a consortium of professional organizations. This expertise will help provide knowledge experts to transform this industry in the next decade. However, not every professional wants to specialize in BEM. If you want to design buildings and incorporate the most energy-conscious methods into the design without becoming a BEM expert, then this book is for you—yes, you—the architect who wants to make smart decisions about energy in buildings.

This book seeks to inject BEM into architectural design, helping students and professionals to understand the workflow, leverage it to make decisions, and ultimately reduce the energy footprint of their building designs. The energy modeling process is not unlike the one we use to design: You start with some basic information and a few assumptions and go. However, the difference with BEM is the amount of upfront input required to run a simulation. What energy modeling software requires one to know in advance of producing results is challenging and can hamper the productivity of the design process. In this book we will show how to combine these workflows and leverage them in concert with design to make smarter decisions about a building's performance.

As part of designing to reduce energy consumption, what the reader can take away from this book is a framework for making productive energy-saving choices during building design. Specifically, this book discusses four key concepts that designers should incorporate in their practice, and students use in their design studios. First, a fundamental review of energy efficiency and climate helps demonstrate how design elements inform energy-saving architectural design practice. We review a range of design elements common in building design for a variety of climate zones. Second, we discuss fundamental elements critical to the energy-efficient design of buildings. Using BEM, we show how these elements have the

potential to reduce a building's energy consumption. Third, we review how to create computationally based parametric models and means of testing and optimizing each element with energy modeling during design. Finally, from these results we provide an energy pattern guide for a range of building sizes.

Inspired by Victor Olgyay's 1963 book *Design for Climate*, this book looks to advance the body of knowledge about passive solar bioclimatic design by using BEM and parametric modeling. The foundation for this book respects the historic research about bioclimatic design and passive solar architectural strategies. While Olgyay's book focused on residential architecture, the ideas he expressed have been used and explored across the entire discipline. Olgyay quantified the energy implications of design decisions four years before the invention of the modern calculator. We hope the ideas in this book hold equal relevance for advancing architectural design into the future.

Now emerging is a disciplinary field somewhere between traditional architectural design and engineering for high-performance buildings. What it is called has yet to be determined, though we've seen, read, and heard it referred to as *design performance analysis*, *conceptual energy modeling*, *building performance*

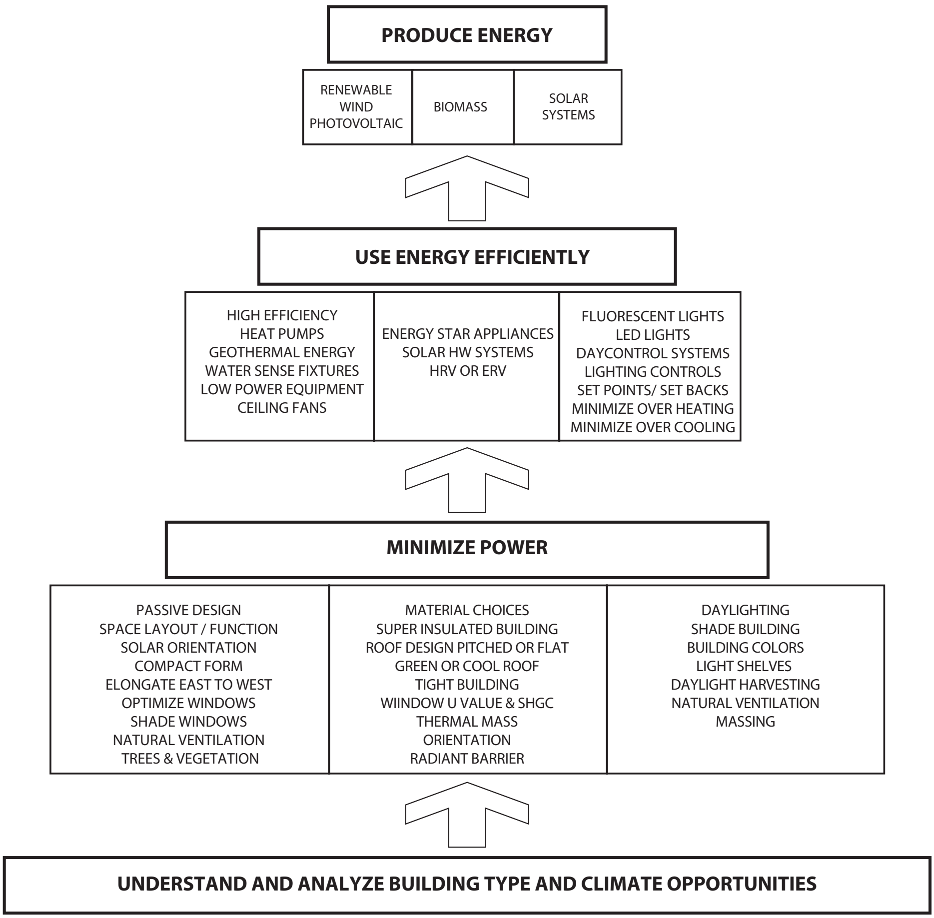

Figure 1.1 **Energy pyramid showing design decisions to maximize architecture's role in reducing our reliance on energy based upon building type and climate to minimize the need to use power, using energy efficiently, and producing energy.**

modeling, or simply *building energy modeling*. While energy modeling has over the years situated itself primarily within the engineering field, this new use doesn't sit comfortably within the traditional engineering discipline. Architectural offices are doing their own simulations, creating energy models, and hiring consultants to supplement their designs with energy modeling analysis. Therefore, the space to define the methods, timing, sequencing, and operational application of building energy modeling within design is wide open.

The book's focus is on the bottom of this energy pyramid, those measures that minimize our use of energy or power within the building. Illustrated in Figure 1.1, our energy pyramid for building design is partially derived from presentations by Peter L. Pfeiffer, FAIA, and Norbert Lechner. Both Pfeiffer and Lechner speak in their own ways about maximizing architecture's specific role in reducing our reliance on energy. As such, the discussion on BEM in design purposely omits discussing the role of active building elements in using energy efficiently. These elements include the mechanical and electrical systems, controls, equipment, appliances, and fixtures incorporated into a building. This book focuses on the passive aspects of design.

Why write this book now? The conditions are right for a book that highlights how advances in computation in architectural design have enabled quicker and greater amounts of design feedback. The challenge of having more information lies in what to do with it. Computing power enables all architects and students to produce results using BEM without leaving their desks. Therefore, we ask, to what end? And for what purpose?

Design Process

Not all BEM tools available for architectural design are created equal. Parsing these programs to help differentiate the software is about finding those tools suitable for architects. The American Institute of Architect's (AIA), *An Architect's Guide to Integrating Energy Modeling into the Design Process*,[2] along with other published guides from the Rocky Mountain Institute (RMI),[3] the U.S. Department of Energy (DOE),[4] and software vendors themselves highlight the comparative pros and cons of the various BEM tools. Finding the right tool for the job is dependent on a range of items related to how you design, how your company does business, and the questions you seek to answer. In the examples highlighted in this book, we use several different BEM tools to demonstrate how using BEM for architectural design benefits decision making.

Out of the plentiful supply of energy modeling software options available—formerly highlighted by the DOE and now by the International Building Performance Simulation Association (IBPSA)[5]—few programs are specific to architectural design. Before choosing a BEM tool it is important to evaluate many of its key features to understand what it will tell you, the interoperability of the software related to your design software, what the software uses as a simulation engine (or calculation cruncher),

outputs, user interface, and other specific needs you may have. The tools ultimately need to fit how you design.[6] There is a learning curve to picking up BEM for design, and part of that curve is knowing when and for what purpose BEM can be used.

In a few cases, using BEM for early-stage design decision making, known as design performance modeling (DPM) or building performance assessment (BPA), is helpful to frame this activity. DPM as defined by the AIA, and BPA by Autodesk, is an early-stage model that focuses on various aspects of building design, giving value to and measuring the energy impacts of design decisions. Both are methods for modeling a building's energy performance during design to understand design impact. Since DPM and BPA relate to design decisions and rely on BEM to provide the metrics and measurements, we assume all discussions that follow pertain to modeling design performance for analysis or assessment, and are referred to as BEM.

Early in the design process, BEM is not about compliance or prediction but about comparison: Evaluating the impact that different design decisions might have. Comparisons about different designs, systems, materials, and envelopes spell out different ways buildings could achieve better performance and be more energy efficient. Since there is not necessarily one way that designers could benefit by using BEM early in the design process, we instead propose a cornucopia of options throughout this book. Not all practicing architects fully understand the benefits of BEM to their process, but they see energy modeling as providing answers to common hurdles they encounter. Since knowledge is power, it is helpful to know, for example, what glass types may be ideal for a given situation, but this and other specific items are highly interrelated to many other early design decisions. Specifically, changes in the building geometry will modify the whole building's behavior, shifting its interior climate and ideal material properties. Therefore, there is no ideal answer to determining the building's optimal performance properties, but the solution will continually shift along with the design.

Along these lines, it is key to use BEM to evaluate the right information at the right time. Since there are many complex decisions made about a building's design throughout the design process, we have attempted to provide a framework to help identify what information can be evaluated when in design and in what way this knowledge can aid the design process.

The impetus for the proliferated use of BEM that motivates this focus is to make our built environment more energy efficient, therefore reducing carbon emissions. No two buildings are the same, and what might work well in one climate does not transfer to others. Using BEM enables designers to make better decisions to aid in saving energy and money.

Financial Benefits

There is a business case for the use of BEM in architectural design. There are three different financial areas where savings can occur for existing building owners and

operators, making buildings more resilient in terms of fuel source availability, and making affordable housing more affordable.

BEM can reduce operational expenses related to the energy consumption of buildings, helping to save money for future and current building owners. Using BEM helps identify energy conservation measures (ECMs), along with proper HVAC system sizing for a given project. It is possible to reduce the initial costs of the HVAC system in addition to the long-term costs associated with operating it. Another benefit could include the greater appraisal value of the overall building. Since incorporating daylighting and other energy-saving elements improves the overall building quality, owners can potentially expect a higher resale value. Also, depending on the design, there could be potential increases in employee productivity, retention, and the overall health aspects associated with high-performance buildings.

Energy efficiency can create a building that has the potential to be resilient to future economic shifts, in addition to fuel source uncertainty. As we review in Chapter 2, society's views on energy do change, and the resources we rely on are not entirely stable over the long term. While we often react to a sign that comes too late, proactive planning realizes that nothing is necessarily stable and that a more resilient system accounts for a range of variability. A building that is more energy efficient will rely less on grid-tied energy, and adding renewable energy will further improve a building's resilience.

In residential markets, where the costs associated with utility bills are significant, it is perhaps more helpful to provide resilience in affordable housing. The RMI has identified that affordable housing often has unaffordable energy costs,[7] and energy efficiency can help by potentially reducing those energy costs by 90 percent. This requires a whole-building approach to evaluating the many different conservation measures made possible with BEM.

Architectural Relevance for Professional Readers

The AIA reported progress toward the 2015 goal of reaching 60 percent greenhouse gas (GHG) reductions as part of the 2030 commitment, and in 2013 66 percent of the total gross square feet were built used energy modeling, leaving 34 percent of the buildings constructed lacking the benefits provided by energy modeling. Had the designers used energy modeling, the AIA projected that these buildings could have achieved additional carbon reductions.[8] We support the conclusion that this provides great value to architecture and engineering in measuring their energy and climate impacts; however, we also suggest that energy modeling involves much more than optimizing design against certifications or code compliance, but seeks continual optimization of energy performance throughout the design process.

The 2013 guide by the AIA on energy modeling in design[9] reviews many

of the programs available and their applicability to early design. This list is valuable for those considering using energy modeling. Included later in this book are examples of how to actually use BEM to make design decisions, something the AIA report omits. Another aspect of the AIA guide is the potential for expanding the range of services a company can provide to clients. BEM creates new possibilities, such as post-occupancy services, building operations, facility benchmarking, energy auditing and master planning, deploying renewable energy, and operational standards development.

How to use BEM during the design phase of a building is a bit more complicated than just opening a program and clicking go. In Chapters 4 and 5 we offer advice on how to begin your energy model, different methods for analyzing energy use, and one way of building your simulation with an understood baseline and using BEM for a goal-setting model to forecast the end of the design process.

Educational Readers

In most cases, teaching the design process with a focus on sustainability and high-performance design relies on BEM to help students and educators dig deeper into architectural strategies and outcomes. Otherwise, these strategies remain rules of thumb without measurable impacts or evidence to support their efficacy. While these rules of thumb are well known and have been used for years, they are often climate specific and based on a low level of evidence. In today's evidence-based environment, it is critical to measure impacts related to design decisions that will reduce carbon emissions.

Today, by clicking buttons on a mouse, students visualize, understand, and communicate their design intentions. Though this appendage of a virtual brain allows easy access to information, what degree of understanding do students leverage? I have sat on numerous design reviews at several institutions where prerequisite information about climate is posted on the wall, but is this information referred to and connected to high-performance building design? Similar to the education received by those from earlier generations, each line on a drawing has meaning and purpose to the design intentions embedded within the architecture, and so too must each analysis, virtual gesture, and graph printed from the computer. Because computation enables greater access to information, it requires informational literacy to unlock the larger meaning this data has as part of an architectural design.

In what way should BEM be taught to students? From an academic standpoint, BEM can be a lecture/seminar course that is taught separately from design studios, or it can be taught inside the studio. Having done both over the years, in our opinion, both are beneficial. As a separate course, it affords focus and depth. Though the topic of focus is not well suited to accompanying a design process as found in the studio, as part of the studio it can be instrumental in the design decisions driving the studio project. BEM simply becomes another element among the many others factored into the course-planning process.

This book values the incorporation of measurable decision making based on BEM. Throughout are simple examples of how to use BEM to make key design decisions in measurable ways. Students can benefit from following the use of BEM through the design process followed by professionals. The book is a framework showing a way for buildings to achieve higher levels of sustainability from an energy conservation point of view.

Outline of the Book

Energy Modeling in Architectural Design answers many questions in as simple a manner as possible to provide the architect with the best possible start. Two aspects of this book are important to take away: First, BEM is part of design from the beginning. Using BEM early unlocks the second aspect, which is that BEM allows architects to control important decisions that affect energy implicitly. Therefore, it is key to understand how to use BEM as an integral part of the design process, and what can be simulated to make more energy-conscious decisions. In our opinion, doing so maximizes architecture's role in energy conservation.

The primary item architects control, in addition to the composition of a building, is the process by which it is conceived. There is a wealth of literature regarding the use of BEM for design that discusses early or conceptual design. For the architecture profession, BEM fits into the conceptual/predesign and schematic design phases of a project. Predesign often begins by defining the nature of the building or the client's needs, and helps establish the scale and scope of a project that is then explored in the schematic design phase. Depending on the project's scope and structure, conceptual design can belong to either of these phases. All are considered early points of a building design, in contrast to the construction documentation phase at the end of design, when BEM has historically been used. Therefore, for our purposes, any decision that occurs before a project's construction documentation phase is considered early design.

Reading this book can help improve your knowledge of BEM in architectural design. Chapter 2, *History of Energy Efficiency*, reviews the history of passive solar architecture and places it within a changed marketplace where standards and rating systems provide practice with an evidence base from which to work. We further this discussion in Chapter 3, *Climate Opportunity*, on understanding the climate possibilities created by using energy modeling to parse the weather files and profiles that identify where design might begin. Following this, Chapter 4, *Energy Modeling for Architects*, elaborates on exactly what this process means. Situating energy modeling is important in framing the larger conversation of using BEM in a design process and workflow to improve building performance. Chapter 5, *BEM Baseline*, shows the importance and value of beginning BEM with a known starting point and how said starting point is defined.

Chapter 6, *Passive Solar BEM*, is divided into three sections discussing

the geometric properties of buildings and the fundamental design aspects considering energy, including building orientation, shape, height, and massing. Expanding on these measurable aspects of buildings helps quantify some of the formal qualities for energy modeling. Building on BEM, the building program and energy-related issues, window fenestration, and shading are highlighted and issues of materials are discussed. Many envelope decisions faced by architects are ripe for BEM, additionally a building's program and interior space layout, geometry (building massing, aspect ratio, and proportion), site selection, placement and orientation, window placement and fenestration, and material selection and specification. The chapter discusses these decisions and offers design examples to outline the sensitivity of a building's geometry to its relationship with the other aspects affecting energy performance, related to both the sun and the building's form.

The book discusses our ability to measure many of these design elements concurrently in a simulation and this is the subject of Chapter 7, *Issues with BEM*. Here we focus on how to define parametric modeling operations for the energy modeling of building elements, challenging the notion of whole-building energy analysis for early geometric modeling. This chapter includes a BEM Pattern Guide showcasing a pictorial overview of office building forms to improve performance, demonstrating metrics for various letter-shaped buildings from the L, H, T, and U shapes. As a case in point, Chapter 8 concludes the book with *Project Examples* showcasing several contemporary examples of different building types from different climates.

Since no one building looks exactly like any other, geometry is variable and sensitive to different design decisions, climate, and energy performance criteria. This makes establishing clear rules for how best to design a building for optimal energy performance challenging. However, using BEM as we have done in this book addresses some of the sensitive geometric issues specific to externally and internally loaded building types. Within these two types of buildings, we look directly at the shape and volumetric proportions typical within passive solar design. Additionally, doing so provides an example of how to test design ideas using BEM as part of the design process.

The practice of architecture is rapidly changing due to the political, professional, technological, and climatic forces impacting how buildings should perform. Great care is required to understand the complexity of a building's energy performance. The assumptions and intuition used to produce designs require verification with relevant energy modeling to demonstrate that they do indeed perform as the design intends.

Looking Ahead

One important note about prior knowledge: As this book is written for students of architecture, practicing architects, and engineers, basic information is provided

about building science, thermodynamics, and processes of energy production and consumption. As is the case in our discipline, much of this information may have already come up during your educational background. If not, we have identified other sources of information throughout the book that we recommend using to supplement your knowledge of the principles and issues discussed.

As a profession that designs, engineers, renovates, and operates the built environment, it is imperative that we do so with an eye toward carbon neutrality. If, as Ed Mazria has proposed, all existing and new buildings will be carbon neutral by 2050, we have a lot to do between now and then. Much of this effort relies on the skillset we already possess, but some will rely on new ways of thinking and new tools to get us there.

Building information modeling (BIM) promised to improve the efficiency, quality, and profitability of project delivery. BEM promises to deliver a tool for systems thinking about a building, the active and passive energy performance of building design related to its environment. Looking ahead, BIM and BEM will not stand alone in this effort. Even in a few years' time, something else will emerge that has the potential to transform the industry. Political and social forces or technology may alter our current course as well, as they did in the 1970s or as they are doing now in reaction to climate change. Regardless of the road ahead, intelligent and effective use of BEM in architectural design will improve the energy efficiency and overall quality of the built environment.

Notes

1 Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by R.K. Pachauri and L.A. Meyer (Geneva: IPCC, 2014) 102.
2 Energy Modeling Working Group, *AIA Guide to Integrating Energy Modeling in the Design Process* (Washington, DC: American Institute of Architects, 2013)
3 Ellen Franconi, Kendra Tupper, Black Herrschaft, Craig Schiller, and Robert Hutchinson, *Building Energy Modeling for Owners and Operators: A Guide to Specifying and Securing Services* (Boulder, CO: Rocky Mountain Institute, 2014)
4 U.S. Department of Energy, "Building Energy Modeling," http://energy.gov/eere/buildings/building-energy-modeling.
5 International Building Performance Simulation Association USA, "BEST Directory," www.buildingenergysoftwaretools.com.
6 The Appendix offers a summary of building energy modeling software.
7 Alexis Karolides, "Affordable Housing with Unaffordable Energy Bills," *RMIOutlet*, August 19, 2013, http://blog.rmi.org/blog_2013_08_19_affordable_housing_with_unaffordable_energy_bills.
8 Alec Appelbaum, *AIA 2030 Commitment, 2014 Progress Report* (Washington, DC: American Institute of Architects)
9 Energy Modeling Working Group, *AIA Guide to Integrating Energy Modeling in the Design Process*, 53.

2 An Overview of Energy-Efficient Building Design

This chapter discusses a history of energy efficiency and its evolution influencing building design. It is important that the reader note that the chapter title ends with the words "Building Design." The chapter omits many aspects of energy related to other end-use and production sectors, technology discussions, and renewable energy production. Do not be alarmed at the discussion about energy laws and processes, but instead embrace the nature of this overview as to how society, building professions, and science have shaped the role of energy efficiency in building design over time.

To understand this, one must be aware that energy is one small part of a building. Think of the building as a complex system, incorporating multiple parts and synthesizing them into a complete whole. In this act of systems thinking, you can see how all the different pieces work together. The bigger picture is to maximize the architectural design and its impact to reduce a building's reliance on more complex energy-efficient technology or production systems. The energy parts synthesized in a building have evolved and increased in complexity over the past half-century. Separate from the specifics of the technology, this history of energy efficiency pertains to its societal value and the professional application in building design.

History of Energy Efficiency

What makes today's architecture different from the passive design approach of the past? Look back at the history of architecture. Prior to 1940 only a few wealthy and industrial buildings could afford the large air conditioners of the period.[1] Buildings had to be bioclimatic and were designed based on the local weather, taking advantage of natural ventilation and daylighting. Because of this, local vernacular drove residential designs that could keep their residents comfortable and alive during periods of extreme heat and cold. Active systems for heating were coal stoves or fireplaces, and cooling was perhaps your ice box or a fan.

The facts of climate informed the local architect's expertise and the formal morphologies of buildings that were specific to their climates and could respond to the needs of their occupants. One can see a stark contrast between climate-adapted and climate-rejecting buildings when standing in front of Independence Hall in Philadelphia. In the foreground is a building designed to maximize natural light and ventilation, called a climate-adapted building.[2] Specifically, the assembly rooms on each side, north- and south-oriented, have eight-foot tall, wide double-hung windows with integrated interior shutters to close off the interior on a cold night. The four-foot high sills bring the total height of the window to 12 feet off the ground. The width of the room from window wall to window wall is around 44 feet. The common rule of thumb for daylighting is 1.5 to 2 times the window height, making the effective daylighting in this space 16 to 20 feet, more than adequate for daylighting the interior on a cloudy day. Anyone familiar with the authoring of US independence will recall that it was very hot in Philadelphia during this time, and though the founding fathers would likely have appreciated air conditioning, the point is the embedded daylighting in the building.

Across the street from Independence Hall is Penn Mutual Tower by Mitchell/Guirgola at 501 Walnut Street. In contrast to Independence Hall, this modern glass-clad office tower was completed in 1975 for the Penn Mutual Life Insurance Company. Tucked in behind John Halivand's Egyptian revival façade, the visual relationship juxtaposes a design relying on electric lighting and central air conditioning against a building from a period when these luxuries were absent. Instead of the east-to-west elongation found in Independence Hall, the Penn Mutual Tower stretches north to south, with full curtain walls of glass on both the north and south façades. Punched recessed openings face east, with vertical ribbons of glass running up the façade. The floor-to-floor height appears to be 14–16 feet, which would allow light to penetrate only about 20 feet into the 80-foot deep floor plate. This makes it impossible for employees to work exclusively by daylight. In addition, the windows do not open.

We are not arguing for historicism or design without modern amenities; our goal is to highlight the pre-systems building form and design strategies that maximized architecture's bioclimatic response for habitation. A climate-adapted design is one in which the solar building becomes a new form of energy consciousness embraced as architectural design criteria.[3] In contrast with what the Solar Energy Research Institute (SERI) in 1985 defined as the climate-rejecting building—where form and envelope serve solely as barriers between climate and conditioned space for environmental-control purposes—the climate-adapted building uses environmental-control techniques based on architectural and engineering concepts to integrate the building within its climate.[4]

Other notable climate-adapted buildings designed during the pre-systems era are highlighted by Michael Holtz, one being the Wainwright Building by Louis Sullivan. This project lacked both mechanical cooling and humidity control, with

incandescent lighting being available but costly.[5] The Wainwright resolved daylighting and natural ventilation requirements using a U-shaped form to locate workers near the exterior walls where lighting and air penetrated. These early office buildings created productive interior environments without electric lights, utilizing daylighting and unconditioned natural ventilation.

Somewhere in between the climate-adapted and the climate-rejecting building is a hybrid, which capitalizes on the benefits of bioclimatic design, along with the new materials and technology of today's mechanical and electrified buildings. An early precursor of the hybrid is the Larkin Building by Frank Lloyd Wright, which resolves issues affecting daylighting and work environments alongside early mechanical ventilation. One of the first so-called hermetically sealed buildings, the Larkin Building allows internal mechanical equipment to handle its thermal and ventilation needs. Its main feature, however, is a glazed central atrium to pull daylight into the interior for the work areas. While the usable floor plate of the building is a rectangular courtyard, the glazed atrium in the middle reduces the exposed surface area, some 30 percent less than the Wainwright building's thermal boundary.[6]

Designers in this pre-systems era understood the necessity to design with and for the local climate. Gaining expertise through repeated experience and living and working in the same geographical location helped them understand their specific bioclimatic approach to design. A lot has changed, however, and the luxury of gaining deep, local expertise on what works in a specific location is not available in today's global practice. Firms work across geographical locations, in different climates with different people, politics, and clients; rules of thumb developed in Dallas do not transfer to Boston. To unpack these changes we need to look back and see where and how our current building design practices evolved.

Energy efficiency in our society has evolved through a variety of ways. These routes are political, set by the federal government or professional organizations, both of which affect industry standards. These forces shape and motivate widespread changes in the way we build buildings. Next, there is science—how we understand energy and building physics changes quite rapidly. Much of the research and methods of calculation have changed since the 1960s, when some of the first energy-conscious design literature emerged. Finally, there is the market approach: As the costs of new technology drop, that technology tends to see increased adoption and implementation in the building industry.

A major shift occurred during the 1970s. Put yourself in the shoes of the 1970s architect and you would find yourself designing buildings to incorporate conditioned air and mechanical ventilation. However, there was no such thing as building science to understand material permeability, vapor diffusion, or infiltration. Building insulation consisted of early mineral wool, if insulation was used at all. Industry standards were just surfacing, and energy codes were not at all a consideration. Looking back through history helps to situate how we got to where we are today.

Federal Policy

The federal government has led on energy-efficiency issues through its reactions to larger global and societal issues, the prime example of which was how to handle the energy crisis resulting from oil shortages in 1973. This event shifted the U.S. to look holistically at energy, and in 1975 Gerald Ford signed the first national Energy Policy and Conservation Act (EPCA), which was followed in 1976 by the Energy Conservation and Production Act (ECPA).[7] The ECPA marked the first time that commercial and public buildings became a target for energy conservation, and it led to weatherization programs for low-income homes.[8]

The original legislation granted the president—subject to congressional review—the ability to impose rationing and to reduce demand for energy through the implementation of energy conservation plans. Among other items, the EPCA set up the strategic petroleum reserve, increased the fossil fuel supply, conserved energy through different programs, and regulated energy use. In addition to holding a conservation and regulatory authority, the president could set motor vehicle fuel efficiency and expand the national fuel supplies from a variety of sources. Finally, the EPCA passed into legislation the verification and reliability of energy data.[9]

The meat of the initial EPCA established energy-efficiency requirements for motor vehicles and consumer products. Therefore, under the Act, regulation was possible for any consumer product that consumed energy, whether that energy was electricity or fossil fuels. The EPCA elaborates on enabling the capability to limit the quantity of energy consumed at the point of use (defined as energy use), and the ratio of useful output to the energy use (defined as energy efficiency). These two taken together constituted the energy-efficiency standard that prescribed a minimum level of energy efficiency for relevant consumer products.[10]

We see this everywhere today with the Energy Star labels on appliances, and though these labels were the result of later legislation, they embody the labeling of estimated annual operating costs that began with the EPCA. Prior to this, no such externalization of energy data was required. Consumer products covered included refrigerators, freezers, dishwashers, clothes dryers, water heaters, single-room air conditioners, home heating, televisions, kitchen ranges, washing machines, humidifiers, central air, and furnaces, as well as any household products that were likely to exceed 100 kwh per year.[11] The EPCA also enabled target setting to be effective by 1980; products in 1980 were to be a minimum of 20 percent more energy efficient than they were in 1972.[12]

Outside of specific vehicular and consumer-product energy efficiency, the law required states to prepare their own energy conservation plans. Each state was to set goals for energy reductions of at least 5 percent or more of the energy projected to be consumed in the state in 1980.[13] The plans developed by each state included mandatory lighting efficiency standards for public buildings, multi-modes

of transportation, mandatory standards and policies relating to energy-efficiency procurement practices, mandatory thermal efficiency standards, and insulation requirements for new and renovated buildings (though, ironically, not for those owned or leased by the U.S. government), along with a traffic law to allow right turns at a red light.[14]

Perhaps the federal government opted to allow states to handle building energy efficiency directly because regional climatic conditions would require different insulation levels and thermal efficiency, and allowing states to put forward how they saw investing in energy efficiency would allow them to consider local differences in material uses and construction practices. In line with local issues, states also distribute federal dollars and are knowledgeable about the technological capacity to deliver, the financial feasibility, and available resources, as well as being able to take population issues and economic development into account to comply with the National Energy Plan.[15]

Finally, provisions of the EPCA targeted major energy-consuming industries to identify the top ten industrial consumers of energy for further energy reductions.[16] The government also exempted those corporations that had plans in place for a voluntary reporting program.[17] The plan concludes with the development of energy-efficiency standards (similar to those requested from the states) for federal buildings and agencies. Along with thermal efficiency, standards and insulation requirements included limiting hours of operations, controlling thermostats, and procedures for replacement and retrofitting,[18] the goals being to encourage energy conservation and energy efficiency through a public education program and through the government's own operational and procurement policies.

The lasting legacies of the 1975 EPCA are more numerous than identified here, as we've omitted much of the legislation's petroleum and vehicular aspects to focus on buildings. However, the EPCA also contains numerous mentions of energy information disclosure, requiring the reporting of anyone who produces, processes, refines, transports, or distributes energy resources.[19] Today we see this in the Energy Information Agency,[20] a powerful collection and reporting tool. From consumer products to buildings, the EPCA set out to make the country more resilient in the face of an uncertain future.

President Carter followed these actions in 1977 with Executive Order (EO) 12003 and his own National Energy Plan that identified energy efficiency as its cornerstone because it was the easiest, cheapest, and most practical way to conserve energy. This EO was another important policy Act that shaped the nation. During his term in office, Carter also set up the Department of Energy in response to the energy crisis and a need for unified energy planning.

In EO 12003, President Carter expanded the impact of energy efficiency further within the built environment to include a ten-year plan for reducing governmental building energy use in federally owned offices, hospitals, schools, prisons, multi-family dwellings, storage facilities, and other buildings where energy-efficiency performance goals were feasible.[21] Looking at the totality of the federally

owned buildings, the order set a goal of a 20 percent reduction in the average annual energy use per gross square foot of floor area in 1985 from the average energy use in 1975.[22] After EO 12003, all new buildings were to be 45 percent more energy efficient.[23]

Perhaps not as well-known was the desire of this order to establish an effective method for estimating and comparing lifecycle capital and operating costs for federal buildings, including residential, commercial, and industrial types. Lifecycle cost was defined as the total cost of owning, operating, and maintaining a building over its economic life, including its fuel and energy costs.[24] Another feature of EO 12003 required energy audits to identify the type, size, energy-use level, and major energy-use systems within existing federal buildings.[25]

The National Energy Plan went before congress in 1977,[26] contributing building energy-efficiency measures beyond those already identified in past legislation. Examples of these measures include making tax credits available for homeowners and businesses to conserve energy, delegating a rural weatherization program to the Secretary of Agriculture, creating federal grants for nonprofits and public schools to install energy conservation measures, insulating residential one- and two-family dwellings prior to their sale, and reinforcing the 20 percent energy savings for existing federal buildings and 45 percent for new federal buildings.[27] In addition to the buildings themselves, the National Energy Plan included investments in technology such as solar energy for water and space heating, and test procedures for home appliances, along with continuing existing laws to establish labeling requirements.

Outside of building requirements, another important aspect of the National Energy Plan was maintaining air-pollution control standards while using coal power plants. Contrary to our impetus today to reduce coal-fired power, in 1977 the nation reacted to shortages of petroleum products by substituting coal as an energy source. While Carter established the foundation for the nation's energy-efficient approach toward buildings, he also set in place a legacy of coal consumption we are now attempting to shift away from.

Congress approved the National Energy Conservation Policy Act on November 9, 1978, making many of Carter's ambitions a reality. The legislation ushered in energy conservation programs for residential housing, schools, hospitals, and buildings owned by local governments, along with energy efficiency for consumer products and standards for automobiles.[28] Other federal energy initiatives included solar heating and cooling, solar energy for hot water, photovoltaic utilization, and state energy conservation plans, among others.[29]

Following the National Energy Conservation Policy Act, in 1979 the first Commercial Building Energy Consumption Survey (CBECS) began collecting information on commercial buildings and their energy-related characteristics. In this national sample survey, interviewers collect building characteristics and energy usage data, and require building owners and managers to respond or give their energy provider's information. The survey also solicits follow-up information

from energy suppliers that provide electricity, natural gas, heating oil, and district heat. Since its inception, the CBECS has been completed ten times, with the most recent survey occurring in 2013.[30]

It would be another decade before any additional federal action was taken on building energy efficiency. The Energy Policy Act of 1992 (EPACT92) addressed buildings and, for the first time, energy codes.[31] The Act encouraged voluntary adoption of a model energy code to meet or exceed the current model building codes, and energy-efficiency standards for federal buildings meeting ASHRAE's 1989 90.1 Standard. This legislation tasked states to have commercial energy efficiency in their codes based on ASHRAE's 90.1 Standard within a two-year period.[32]

The code section of EPACT92 elaborates on establishing codes that are cost-effective and builds on the expertise of various stakeholders in the fields of home-building, utilities, energy efficiency, building codes, and low-income housing, among others. Federal buildings were to adopt energy-efficiency standards in addition to the model energy codes,[33] and the Act provided support for a voluntary residential rating system.[34] Building energy efficiency focused on multi-family and single-family housing with energy-efficient mortgages incorporated under the National Affordable Housing Act.[35]

The residential aspect of EPACT92 transformed energy efficiency for housing, specifically requesting a uniform voluntary rating system for homes based on the 1992 model energy codes.[36] In 1995, the Environmental Protection Agency (EPA) launched Version 1 of the Energy Star certified homes program.[37] Similarly, EPACT92 helped to increase attention to the Home Energy Rating System (HERS) from the Residential Energy Services Network (RESNET) organization, formed from the insurance agencies responsible for evaluating energy efficiency in homes.[38] HERS began in the 1980s in response to a lack of ways of understanding energy use in residences and has today become one of the most widespread home energy rating systems.

In 1999, President Clinton issued EO 13123, Greening the Government Through Efficient Energy Management.[39] EO 13123 recognized that the federal government is the largest consumer of energy and owns or operates some 500,000 buildings across the U.S. The order set goals to reduce greenhouse gas (GHG) emissions through buildings by 30 percent by 2010 compared with 1990 levels.[40] It also asked federal agencies to reduce their energy consumption and expand the use of renewable energy within their buildings.[41] These energy reductions and goals were based on source energy and determined by evaluating lifecycle costs, conducting facility energy audits, implementing energy management strategies, procuring Energy Star and other energy-efficient products, and striving to meet the Energy Star building criteria for energy performance.[42]

Following the EO, the Energy Policy Act of 2005 focused on energy efficiency in federally owned buildings, setting targets for energy reductions (for example, 10 percent savings by 2010), energy-use measurement and accountability,

funding research into advanced building efficiency,[43] and updating the reference codes applicable. The next notable influence on building energy efficiency was the 2007 Energy Security Investment Act, of which Section 401 outlines the federal initiatives for energy and buildings.[44] A noticeable change in this legislation is the incorporation of high-performance, zero-energy, and healthy buildings into the federal mindset. This terminology appeared first in 2003 to distinguish differences between building construction methods.

In 2009, the American Recovery and Reinvestment Act (ARRA) pages H.R. 1–24 to H.R. 1–33 outline issues under the purview of the U.S. Department of Energy, specifically that for each state to receive funds they must enforce construction practices that meet or exceed the 2007 ASHRAE Standard 90.1.[45] The Act allocates a large amount of funds to weatherization programs on existing residential buildings, focusing mainly on low-income housing and dwellings, and includes energy-related topics such as renewable energy, smart grids, new research, and an array of others. As summarized by the DOE:

> The American Recovery and Reinvestment Act of 2009—commonly called the "stimulus"—was designed to spur economic growth while creating new jobs and saving existing ones. Through the Recovery Act, the Energy Department invested more than $31 billion to support a wide range of clean energy projects across the nation—from investing in the smart grid and developing alternative fuel vehicles to helping homeowners and businesses reduce their energy costs with energy efficiency upgrades and deploying carbon capture and storage technologies. The Department's programs helped create new power sources, conserve resources and aligned the nation to lead the global energy economy.[46]

Today, we have moved from initiating energy efficiency through incentives, code adoption, and programs to measuring and monitoring energy efficiency's progress and proliferation across the built environment. The Energy Efficiency Act of 2015 accomplished this by enabling further data collection through the CBECS to include data centers, trading floors, and restaurants; by expanding Energy Star into specific tenant-by-tenant spaces; and by measuring the energy and cost implications of processes, procedures, and policies to improve the energy efficiency of commercial buildings.[47] Another feature this bill established is a national energy-benchmarking database,[48] which may well have become a reality by the time you read this book.

Policy plays a valuable role in shaping the nation's energy consumption and conservation approaches. The legislative actions themselves, however, did not create something out of nothing, but more often than not pushed forward vital programs, practices, and policies both promoted by other organizations and founded in scientific research.

ASHRAE

Practicing engineers and architects designing high-performing buildings are likely well aware of the ASHRAE standards and guides. ASHRAE defines many of the standards for the design of buildings and their systems, playing an essential role in guidelines for building climate, energy efficiency, ventilation, and the design of high-performance green buildings. Many of the standards outlined by ASHRAE interrelate to influence important aspects of our built environment.

ASHRAE has evolved as an organization alongside the technological inventions most crucial for society. While the organization's handbook exists today as a complex array of technical guides, standards, and methodologies, it was first published in 1922 by the American Society of Heating and Ventilating Engineers (ASH&VE) under the title *Heating and Ventilation Guide*, and since then has undergone a rich transformation:

> The purpose of this new addition to the Society's publications is to provide the engineer, the architect and contractor alike, with a useful and reliable reference data book relating to the art of heating and ventilating. A wide range of data within the scope of the field is presented and every effort has been made to present the material in a practical and useful manner.[49]

Beyond the specific handbook, ASHRAE publishes various standards. ASHRAE Standard 90, first published in 1975, focused on the energy-efficient design of new buildings. Updated in 1989 and retitled "Energy Standard for Buildings Except Low-Rise Buildings," it became a methodology for creating an energy consumption baseline for whole-building energy modeling before being renumbered ASHRAE Standard 90.1 in 2001. The methodology (known as part of Appendix G) is necessary to establish the proper simulation for calculating energy consumption and predicting the potential energy savings of design changes. Appendix G is essential for anyone using energy modeling (which is why Chapter 5 of this book focuses on building a baseline), and outlines expectations for simulations and the requirements for energy modeling tools.

Some of the key takeaways from Standard 90.1 are that one should use the same Building Energy Modeling (BEM) tool to simulate energy use while also using the same weather data and energy rates throughout. Simulation programs must be approved and capable of simulating 8,760 hours of weather data, hourly changes to dynamic aspects of the building's operation, thermal mass, ten or more thermal zones, part-load and efficiency-correction curves, air-side economizers, and the building characteristics outlined in the standard.[50] Given these requirements, programs created for architectural designers and students of architecture might not be adequate for compliance requirements creating the baseline model.

Related to Standard 90.1 are ASHRAE standards that consider the design of the interior environment, such as Standard 62.1 dealing with ventilation

and indoor environmental quality, and Standard 55 on thermal environmental conditions for human occupancy. Here, providing comfort is key to sustainable building design, and both standards help engineers and architects design and maintain environments that are safe and comfortable for our habitation.

In 2009, Standard 189 helped define the design of high-performance green buildings. As with most of the ASHRAE standards, collaboration with key stakeholders such as the International Code Council (ICC), the U.S. Green Building Council, Illuminating Engineering Society (IES), and the American National Standards Institute (ANSI) was an outcome of the Building Environmental Impacts and Sustainability technical committee. The effort reflects a comprehensive document with adoptable language to provide the minimum acceptable level of design criteria for high-performance green buildings. It encompasses the building and site from design, construction, and through operations to reduce the energy and environmental impacts. The provisions in the standard address site sustainability, water-use efficiency, energy-use efficiency, indoor environmental quality, and the building's impact on the atmosphere, materials, and resources.[51] As a more comprehensive standard than those focused on just climate, ventilation, or energy, Standard 189.1 deals with the far-reaching effects that buildings have on our environment.

At the time of writing this book, ASHRAE is finalizing Standard 209, Energy Simulation Aided Design for Buildings Except Low-Rise Residential Buildings, providing minimal requirements for energy design assistance with BEM for simulation and analysis. This standard articulates a generic modeling cycle for various points in time during the building's design, construction, and operation. Architects and engineers should be able to leverage the standard to clarify products and services. Rating and certifications systems will also benefit though adopting the standard.[52]

Climate (discussed in the next chapter) is key to any starting point for design. Aiding our scientific understanding of climate's relationship to buildings, ASHRAE offers a climate data center online.[53] Here, one can locate references for weather, standards, and guides. Specifically, ASHRAE Standard 169 also serves as a comprehensive source of climate data for the building design community, outlining climate maps of the world and providing data for 5,564 locations.

Science

Research into energy efficiency in the built environment precedes both the establishment of ASHRAE and the federal government's energy policies. The earliest research dates to the 1950s and continued through the 1980s, due to research investment by the federal government and other agencies. The biggest difference was the participants. The earliest researchers included scientists with backgrounds in physics, biology, and nuclear science alongside architects and engineers. The

entities in charge ranged as well, from universities to research labs to adventurous professionals of the day.

National laboratories such as the Los Alamos National Laboratory and universities such as MIT paved the way in the mid-1950s to early 1980s. Los Alamos supported the evaluation of test rooms, boxes, and projects for evaluation. Douglas Balcomb highlights the Los Alamos research completed between 1976 and 1983 in his book, *Passive Solar Buildings*,[54] sharing the outcomes of the work and the effort required in connecting the disparate but passionate communities involved. Their research helped to validate early experiments by architects and engineers, along with solar innovations such as the Trombe wall.

A ten-volume series from the MIT Press[55] summarized most of the passive solar research from 1975 to 1992. These ten books touch on the movement's history, resources, and economics, along with MIT's research into building energy, solar collectors and storage, active solar systems, passive solar buildings, passive cooling, solar building architecture, and solar thermal technology. Douglas Balcomb's text also describes MIT's testing evaluations of walls, windows, and heat storage alternatives. Alongside the results of the research came methods and math to calculate storage in thermal mass, the thermal transfer of energy through materials. Early computers enabled complex calculations over different periods of time and during peak heating and cooling periods. This ability to calculate thermal performance helped scientists and researchers describe the behavior of passive solar features, along with helping to project energy savings and the degree of thermal comfort achieved.

Princeton supported research by Victor Olgyay for the U.S. Housing and Home Finance Agency in the 1950s. His work was published in several articles for *Architectural Forum* and in two books by Princeton University Press: *Solar Control and Shading Devices* in 1957 and *Design with Climate* in 1963.[56] One can see the importance of Olgyay's work in buildings of the period that incorporate the different shading devices of the time, as modernists from Aalto, Neimeyer, Neutra, Corbusier, Rudolf, Breuer, and Nervi embraced climate in ways that differed from the climate-rejecting styles of Mies van der Rohe and SOM. On the contrary, Olgyay's writing gives life to climate-adapted design strategies by demonstrating how buildings relate to the sun.

Alongside the science to validate how a whole-building dynamic works was research into specific passive solar systems, primarily for heating using direct-gain, thermal-storage walls, and sunspaces. Edward Mazria, whose *Passive Solar Energy Book* was published in 1979,[57] serves as the early pioneer of designing and utilizing passive solar aspects. Mazria's book summarizes much of the decade's research in a concise volume, and today there are hundreds of look-alike copies out there on a variety of approaches for passive solar home design. The beauty of Mazria's book is the way in which he walks readers through each item in a very clear and additive fashion. When he began his work four years earlier, however,

there was very little information on how to achieve much of what his book highlights.

Important as well during this time was the work of Ralph Knowles at Auburn University and the University of Southern California, summarized in his 1974 book, *Energy and Form*.[58] His work was one of the first to apply solar principles, beginning in 1962, to the shape of buildings and the urban form. The work established methodologies for students and architects to shape energy-conscious forms and urban spaces, creating forms that avoid solar radiation or allow penetration of the sun into dense urban forms. Many cities established policies based on these basic principles, and today Knowles's research continues to shape energy-efficient buildings and urban forms.

The works by Olgyay and Mazria, however, focused primarily on residential buildings. In 1985 the SERI published *The Design of Energy-Responsive Commercial Buildings*.[59] Instead of relying on the rules of thumb that many of the passive solar books sought to define for the narrow field of residential design, *The Design of Energy-Responsive Commercial Buildings* discusses a framework and process for designing climate-adapted buildings. Additionally, the authors highlight historic examples, case studies, and speculative examples of approaches to commercial buildings to achieve energy savings. The goal was to make a case for how to approach specific climates, design a bioclimatic building, and not rely entirely on active mechanical and electrical systems.

In addition, during this early heyday of passive solar research the AIA Research Corporation worked with different federal agencies to develop guidelines and show the applicability of the science for homebuilders, owners, and design professionals.

AIA Research Corporation

A pivotal entity in the development of passive solar building technology is the AIA, which created the AIA Research Corporation in 1972 to enable funding from the federal government for research. Their work primarily focused on the applicability of the passive solar research completed by scientists. These publications have a lasting legacy to explain the methodologies for assessing and understanding local climates, as well as how to incorporate direct, indirect, and isolated passive solar gains for heating by explaining the outcomes of the science and case studies of actual projects. Their publications and guides are available in libraries across the U.S. and some are archived online.[60]

The AIA Research Corporation's publications helped make accessible the ideas of passive solar design primarily for the residential market. Alongside these were design competitions run and funded by the federal government to motivate homeowners and builders to take advantage of the methods researched and promoted in the publications.

In digging around our library shelves for AIA-related publications on energy and passive solar design, I found the following:

1974	Energy Conservation in Building Design
1975	*Energy*: AIA Energy Notebook v.1
1975	Solar Heated Houses for New England and Other North Temperate Climates by Mass Design
1976	Solar Dwelling Design Concepts
1976	Early Use of Solar Energy in Buildings
1977	Capturing the Sun: Designs From an Architectural Student Competition
1977	Basics of Solar Heating & Hot Water Systems
1978	Regional Guidelines for Building Passive Energy Conserving Homes
1980	A Survey of Passive Solar Homes
1980	*Energy*: AIA Energy Notebook v.2
1981	Energy in Architecture
1988	The Energy Design Research Series: AIA/ACSA Council on Architectural Research
1989	*Energy Design for Architects*, edited by Alexander Shaw for the AIA

If we trace the lineage of the work we can see quite clearly the early research by Los Alamos, MIT, and Princeton emerging in books by Victor Olgyay, SERI, the AIA Research Corporation, Edward Mazria, and many more to build an impressive body of literature on designing climate-adapted architecture. However, one will easily notice the sudden gap between 1981 and 1988 and wonder: What happened? Though we are not historians, the literature states that federal funding for these research initiatives dried up around this time, causing the momentum for many of these concepts to disappear as well.

Perhaps, as is too often the case, this early information has been lost, forgotten, or eclipsed by technological advances. Current textbooks for building construction or mechanical design for buildings often reduce sustainability to a footnote or a single chapter, with the focus instead on the technical nature of systems, equipment, materials, and the technological aspects of the building. While important, these technological advances over the past half-century in many ways overshadow the passive solar principles in building design. This is not to suggest that their relevance is no less important; however, the impact of passive solar energy saving has diminished with more efficient mechanical systems, airtight and super-insulated envelopes, higher-performing windows, and better operational practices. Fortunately, understanding how to design with climate will always be a relevant and necessary partner for good design. Contemporary works such as Ken Yeang's *Ecodesign*[61] and Tom Hootman's *Net Zero Energy Design*[62] carry on the legacy of these early authors, addressing issues of biology and science in the way

we approach the design of our buildings. In addition, today's marketplace for practicing architects and engineers is full of ways to measure and certify the performance of our built environment.

Certifications and Rating Systems

Today, the number of different ways to measure the sustainability of our buildings can feel a bit overwhelming. Should we call a building "a high-performance building," or simply "a green building?" Perhaps your goal is a net-zero energy building, or how about passive buildings, or your flavor-of-the-week building? Whatever you might think about sustainability or what to call your building, it is obvious that much in the U.S. has changed since 1970. What was once a long road to implementing energy efficiency into our buildings is now measured through a wealth of different certifications and rating systems. It was in the mid to early 1990s that one of the first sustainable building rating systems, known as BREEAM, emerged in the UK. Following BREEAM are many updates, versions, and imitations, which up to now have been a dominant force for shaping the built environment, whether you seek LEED certification, wish to embrace the Living Building Challenge, or go the route of Energy Star Buildings or ASHRAE's Building EQ.

Regardless of one's specific choice, measuring building performance is the ultimate goal. Using comparable energy metrics based on established design standards (often ASHRAE 90.1) creates an effective understanding of how buildings are expected to perform. However, some of the most stringent systems report actual operational energy use after a period of a year or more. This provides the most reliable measure of energy performance by taking away the mystery. Often, the criticism of using BEM to simulate energy use is the reliability of this method compared with a building's actual operational energy use. While having the goal of designing a building that meets or exceeds codes is noble, achieving this goal and proving performance is even better. Next, we'll discuss a wide-ranging list of certifications, models, and standards in use today.

BREEAM

As a leading sustainability assessment method for master-planning projects, infrastructure, and buildings, BREEAM addresses a number of stages such as New Construction, Refurbishment, and In-Use. Globally there are more than 535,600 BREEAM-certified developments, and almost 2,218,600 buildings registered for assessment since the organization was first launched in 1990.[63]

This rating system helps developers, builders, architects, and engineers to manage, to excel, to innovate, and to make effective use of resources. BREEAM

values sustainability as a focus to make its certification attractive to investment and generate a healthy, sustainable environment. To promote best practices for sustainable development, BREEAM's technical standards and processes are comprehensive and scientifically based.

LEED

LEED, or Leadership in Energy & Environmental Design, is a green building third-party certification program that recognizes building achievements. Building projects must meet prerequisites and earn points toward different levels of achievement to be certified. Different scales of certification exist with unique and overlapping points available, tailored to the project type. LEED has and continues to transform the way we think about buildings and communities.[64]

Green Globes

The Green Globes system is sold as a revolutionary building environmental design and management tool. Using an online assessment protocol, rating system, and guidance for green building design, operation, and management, Green Globes provides interactive, flexible, and affordable market recognition of a building's environmental attributes through third-party verification.[65]

Living Building Challenge

The Living Building Challenge is a building certification program, advocacy tool, and philosophy promoting a sustainable built environment. It acts to address the limits and the end-goal of sustainability. The specific challenge is built on seven performance categories called Petals: Place, Water, Energy, Health & Happiness, Materials, Equity, and Beauty. Each petal is broken down into other categories and can be applied to any scale and location of a building project.[66]

Building EQ

Building Energy Quotient (bEQ) is a building energy rating program that provides information on a building's energy use. bEQ is part of ASHRAE methodologies and standards derived from the experience of qualified practitioners. Given ASHRAE's history and expertise, the rating system provides building owners and operators with reliable results. The system uses two workbooks to evaluate designed energy and in-operation performance.[67]

Energy Star

Energy Star is part of the federal government's EPA portfolio to certify buildings that save energy and money, and help protect the environment by generating fewer GHG emissions than typical buildings. A building must meet strict energy performance standards set by the EPA. Specifically, to be eligible for Energy Star certification, a building must earn an Energy Star score of 75 or higher, indicating that it performs better than at least 75 percent of similar buildings nationwide. Designers or building operators use the Portfolio Manager to define a target and determine the Energy Star scores for many types of buildings. The Energy Star score accounts for differences in operating conditions, regional weather data, and other important considerations.[68]

Building Asset Score

The U.S. Department of Energy's Building Energy Asset Score focuses on commercial and multi-family residential buildings using a standardized tool for assessing their physical and structural energy efficiency. The score is a simple rating that enables comparison among buildings and provides feedback into energy-efficiency upgrades.[69]

Design Guides for Energy Efficiency

Developed by a committee of organizations behind several of the standards listed above and pulled together for the U.S. Department of Energy, the *Advanced Energy Design Guides* (AEDGs) provide both a prescriptive and performance pathway to reach energy efficiency at levels 50 to 60 percent better than current practice. The guides focus on specific building types and sizes and cover both new construction and renovations.[70]

These publications are intended to accelerate the construction of energy-efficient buildings by providing prescriptive solutions for achieving significant energy savings over minimum building energy codes. The project has involved partners from the U.S. DOE, ASHRAE, the AIA, the U.S. Green Building Council, and the IES. The guides are published online in a series to provide design guidance to achieve 50 percent less energy than those built to the requirements of the ANSI/ASHRAE/IES Standard 90.1-2004 commercial code, and are specific to prominent building types across each of the eight U.S. climate zones.

Other guides exist, such as those for *Energy Performance Based Acquisition in Commercial Buildings, Planning and Financing K–12 Energy Efficiency*, and operations guides to energy savings from plug and process loads. Alongside the energy-efficiency guides are those for BEM from the AIA, RMI, the

Bembook by the International Building Performance Simulation Association, and ASHRAE.

AIA 2030 Commitment

The AIA's 2030 Commitment[71] is a growing national initiative to provide architects with a consistent framework using simple metrics and standardized reporting to evaluate the impact design decisions have on energy performance. Architecture requires thinking differently about sustainable design to meet energy-use reduction targets across the built environment, and buildings are the largest single contributor to the production of GHGs. The 2030 Commitment rallies professionals around a common interest to reduce these emissions.

Energy Codes

ASHRAE Standard 90.1 has been around since 1975, but it was not until 1992 that the federal government required all states to adopt an energy code. In 1994, the International Code Council (ICC) formed to create model codes for buildings. The International Energy Conservation Code (IECC) is one of the I-codes regulating energy in all buildings, whereas ASHRAE's 90.1 is only concerned with commercial buildings. Though adoption of energy code standards is most visible at the local and state levels, not all jurisdictions have been quick to change; in fact, it was not until 2004 that the city of Philadelphia finally shifted to requiring the I-code suite.

International Energy Conservation Code

More recently, the ARRA of 2009 required states to adopt the 2009 IECC before receiving any stimulus funds. This Act also required states to have 90 percent compliance with the energy code by 2017.

The IECC is another important reference for the energy modeling aficionado. The code defines climate zones for various U.S. states and cities and outlines building envelope and mechanical system requirements for prescriptive compliance. It also outlines mandatory requirements for air leakage, hot water, electrical power, and lighting systems, but more importantly, since many buildings do not fit within the prescriptive definitions of the code, the code provides a scope for performance-based compliance based on the total building energy performance. Here, similar to ASHRAE's baseline, is a code-based pathway to investigate the standard reference design, which is a version of the proposed design that is minimally code compliant and used to determine the maximum annual energy-use

requirement for compliance based on total building performance.[72] To meet the code, the proposed design must be less than or equal to the annual energy cost of this reference number. Energy modelers then provide documentation of their methods and results to demonstrate that the proposed design passes the test, along with drawings of the design and the software tools used. Like ASHRAE 90.1, not all BEM tools meet IECC requirements, and teams should take note to be sure their simulation tools meet these minimum expectations.

This short review of IECC is an important one, because newer codes following 2006 IECC and 2004 ASHRAE 90.1 reduce residential and commercial energy use in new construction by 30 percent. Additionally, there are pathways to achieving net-zero energy for both residential and commercial buildings, along with both new and existing retrofits. This is as much of a dramatic shift in our thinking about energy as the one that took place in 1975. The simple fact is that our buildings do not need to consume more energy than they may produce or purchase from renewable energy agreements.

International Green Construction Code

The International Green Construction Code (IGCC) is the first model code to include sustainability measures for the entire construction project and its site, from design through construction, certificate of occupancy, and beyond. The IGCC is expected to make buildings more efficient, reduce waste, and have a positive impact on health, safety, and community welfare. The IGCC is intended for use by specific jurisdictions to create a regulatory framework for new and existing buildings and establish minimum green requirements for buildings and complementing voluntary rating systems. If enacted, the code will serve as an overlay to the existing set of I-codes, including provisions of the IECC and ICC-700, the National Green Building Standard, and incorporating ASHRAE Standard 189.1 as an alternative path to compliance.[73]

The IGCC also includes a clear overview of how one can achieve energy conservation by providing a measurement for energy use intensity (EUI) of a building. Defined as a performance-based compliance pathway for buildings, it uses the simulated or predictive EUI (pEUI). Similar to the Home Energy Rating System (HERS), the **Zero Energy Performance Index** (zEPI) requires a design to demonstrate a score of no more than 51. The index uses an equation taking the simulated pEUI of source energy in kBtu/ft^2/year for the proposed design and divides it by the base annual energy use (EUI) of source energy for a baseline building:

$$\text{zEPI} = 57 \times (\text{pEUI} / \text{EUI}) \qquad (2.1)$$

Currently, the numerical zEPI is a minimal 11 percent savings against the standard reference building. The base annual energy use is the ASHRAE 90.1

baseline for the proposed building, incorporating a few modifications to Appendix G, as spelled out in the IGCC, and verifying that the CO_2 emissions associated with the proposed building are equal to or less than the emissions of the standard reference design.

Future of Building Energy

In 1970, buildings were just beginning to include central air conditioning and asbestos was still a common building material. While a lot has happened between 1970 and today (such as the elimination of asbestos from our products and buildings), has what we know about designing more energy-efficient buildings changed? We continue to weatherize housing in very similar ways and five years after the Energy Policy Act of 2005, the U.S. had only saved 0.7 percent of total energy use.[74] We continue to rely on heating, air conditioning, and ventilation technology to make our buildings habitable. If the future of buildings is zero energy use, then a shift in our thinking is required.

The U.S. Department of Energy desires zero-energy buildings to be a marketable commodity by 2025.[75] Alongside the government's efforts, the AIA's 2030 Commitment has prioritized the carbon neutrality of our built environment for all buildings by 2050. These reduction targets are also included in federal legislation for the stock of government buildings, their goal being a 40 percent reduction by 2025.[76] Achieving these goals asks for the professionals who design our buildings to use a whole-building design process, advanced technology, and renewable energy, along with BEM.

But how much impact does building orientation really have? How much daylighting is available using shading devices? How much more insulation should be added to increase a building's energy performance? These issues are not easily or correctly answered using the same logic as used in passive solar design strategies developed decades ago. In our chapter on climate, we show how the climate consultant software provides recommended design strategies based on the climate; however, it is important to note that the software knows nothing about your building or local site. It is only helpful for setting a path toward choosing the best energy-saving strategy.

Today, a BEM is necessary to make these decisions about the most energy-efficient design approach. There is neither a straightforward approach nor a silver bullet to energy efficiency; it takes a holistic, integrated, whole-building design approach. It also takes not only more than one person, but a truly integrated team. When reviewing the literature discussed in this chapter, one will see that this idea is not new; in its 1985 book, *The Design of Energy-Responsive Commercial Buildings*, the SERI promoted the role of energy analysis in the commercial building design process.

While we have come a long way in energy-efficient building design, there is still a long way to go to achieve architecture that celebrates the natural

environment. It begins with understanding the type of building you are designing and the climate in which it is situated.

Building Load Types

Understanding the climate and the building type at the beginning of the design process helps project teams identify design approaches and energy conservation measures (ECMs). The ECM is not about how the team designs the building, the inherent logic and organization of the bioclimatic building, to be energy efficient. An ECM is commonly an operational activity or active technology used to reduce a building's energy consumption. Given this definition, ECMs are often distinct from passive solar design approaches for an energy-efficient building, and are add-ons made to modify, enhance, or change the design to improve its use of energy. ECMs traditionally evaluated using BEM are discrete, measurable aspects of building design, such as shading devices, different HVAC systems, and others. However, numerous decisions must be made at the start of design about orientation and space distribution, formal approaches that do not lend themselves to the measurability of an ECM, but are nonetheless just as important to how a building uses energy. Therefore, there may be a need to distinguish between those measurable ECMs and those architectural passive design approaches that are inherent to the design.

The early decisions we make or the criteria provided by the client or consultant can drive many of the thermodynamic principles that inform future decisions about the building and its passive solar opportunities. Using principles based on the building type can maximize the architecture's role in energy savings. The first step is defining whether the building type is external-load (skin) dominated, internal-load dominated, or a hybrid of both. The building type, use, and size, along with the climate, will drive this characterization and identify which passive design strategies are appropriate.

Skin-Dominated Buildings

In a skin-dominated building (also known as an external-load dominated building), the energy exchange (the heat loss or gain) primarily occurs through the building envelope—its skin. In this type of building, there are few internal occupants, low lighting, and minimal equipment loads that produce significant amounts of heat. The climates where skin-dominated buildings typically occur are either very hot or very cold, since mild climates do not demand much from the building envelope.

In a skin-dominated building, heat loss and gain occurs across the building envelope. If the temperature is hotter outside than inside, heat will move toward the interior. Due to this movement across the skin, the detailing and design

of the envelope is important. BEM tools in some standalone cases can aid in understanding thermal breaks, infiltration issues, and moisture control across the building envelope. One specific for this task is called WUFI,[77] which can model the hygrothermics of multilayered wall assemblies related to natural weather patterns.

Skin-dominated buildings achieves energy efficiency through high-performance enclosures and super-insulation and, by maximizing passive solar design. Since many of these building types are also smaller, daylighting and natural ventilation are easier to achieve.[78] The design of the building's geometry helps by minimizing the surface area exposed to the hot or cold climate. Balancing these issues alongside the passive design strategies employed saves energy by offsetting the need for heating and/or cooling the building's interior.

Types of buildings that fall into this category are residential apartments, small commercial, non-industrial warehouses, and institutional buildings. Shown in Table 2.1 are several examples of skin-dominated design measures implemented to reduce energy use. The list is not exhaustive, nor should it be absolute. One thing we have found in our work is that every building is different, and while this list represents some common approaches, they may or may not be the best solution given a building's specific situation.

With a skin-dominated building, understanding air leakage or the infiltration rate is vital for the effective evaluation of energy performance. Infiltration—also called air leakage—is the incidental and unintentional movement of air through gaps or cracks in the building envelope. A common measurement of this airflow through the building envelope is air-changes per hour (ACH) at 50 pascals of the building envelope. In skin-dominated residential buildings, infiltration can be one of the most significant sources of heat loss and gain. This makes it essential to verify that the BEM setting for this value follows standard industry-accepted limits. Simulating the ACH measurement too high makes every other choice an architect makes appear unimportant.

Skin-dominated buildings behave differently in hot and cold climates. In a hot climate, the goal is to keep the heat out, whereas in a cold climate you want to keep

Table 2.1 **Common skin-dominated passive solar design approaches.**

Passive solar design	*Goal*	*Effective season*
More windows on south façade	Increase heat gain	Winter
Decrease east and west glazing	Reduce unwanted heat gain	Summer
Shading	Decrease heat gain	Summer
Thermal mass	Store heat	Winter/summer
Compact form	Reduces heat gains and losses	All
Natural Ventilation	Remove heat	Spring, summer, and fall
South facing orientation	Maximize solar energy	All
Elongate along east–west axis	Decrease east–west gains and increase southern gains	All
Thermal zoning	Balance internal heat loads	Winter/summer

the heat in. Therefore, careful design of the building envelope to handle air, water, vapor, and thermal properties is a key part of proper hygrothermal planning and design. Because of how these four items seek equilibrium across the envelope, hygrothermal design is the most important aspect of a skin-dominated building. Simply maximizing insulation without considering the other factors could cause problems.

Internal-Load Dominated Buildings

Buildings that are internal-load dominated have a high density of either occupants, lighting, equipment, or all of the above. This type of building primarily requires cooling year-round regardless of the climate. Buildings that fall into this category are offices, hospitals, heavy-retail buildings (shopping malls), dense educational facilities, and restaurants. In each case, the source of the high internal gains (people, lights, equipment, or all three) will inform the choice of energy-efficient strategies.

These types of buildings benefit from envelope design, shading devices, and fenestration that avoids unwanted solar gain that can add excess heat to the interior. In situations where the internal gains come from lighting, maximizing daylighting and reducing the building's lighting loads will help. Since the building envelope is essentially keeping the heat in, increasing the surface area of the exterior wall may help in colder climates, whereas increasing the roof area can help in hotter climates. Changing the building's geometry may also increase the amount of area for daylighting and natural ventilation. Additionally, earth-coupled cooling and natural ventilation are passive ways to maximize free cooling if the climate is suitable. Integrating the systems and building design to maximize passive solar approaches can help make the building more energy efficient.

Shown in Table 2.2 are several examples of internal-load dominated passive solar design measures to reduce energy use. As with the skin load design examples above, these are common approaches that are neither exhaustive nor

Table 2.2 **Common internal-load dominated passive solar design strategies.**

Passive solar design	*Goal*	*Effective season*
Daylight	Reduce internal gains from electric lighting	All
Natural ventilation	Free cooling	Spring, summer, and fall
Shading	Reduce heat gains	Spring, summer, and fall
Increase wall area	Increase heat loss and daylighting	All
Window U-factor and solar heat gain coefficient (SHGC)	Reduce heat gains	Spring, summer, and fall
Distribution of windows	Balance gains and daylight	All
Thermal zoning	Separate heat-producing uses	All
Daylight zoning	Optimize use and daylight	All

absolute. Passive solar design approaches in internal-load dominated buildings may vary depending on their use, the time of day or month considered, and the climate.

Hybrid

Some buildings are hybrids of skin- and internal-load dominated buildings. The climate and use patterns may at times shift a building from being internal-load dominated to skin-dominated: For instance, schools, when heavily occupied, have high internal loads during the day and sit empty at night. Residence halls and warehouses are others that share enough characteristics of each to oscillate between skin- and internal-load dominated.

In cases of these buildings, pay careful attention to where and when heat gains and losses occur. BEM can be helpful in diagnosing which load is dominating and when to be more strategic about energy-efficient design choices. Combining the strategies above for energy-efficient buildings may be effective for conserving energy by maximizing architecture's role during the different skin- or internal-load periods. Classrooms full of students, for example, may not need to use electric lights if properly daylit, thus reducing the heat gain from lighting. The same space could benefit from pulling down insulated blinds to retain internal heat overnight. This dynamic management addresses both the internal-load- and skin-dominated aspects from day to night use.

Conclusion

The history of building energy efficiency in the U.S. shows an increasing sophistication in what we understand about energy use, its societal importance, and the impact of energy conservation for sustainable or high-performance building design. I hope it is clear by this point that BEM is a necessary tool to advance energy conservation for any building project, whether small or large, internal or skin load dominated. Now that you have an idea of the energy-efficient building characteristics to address and prioritize as part of the design process, next is how BEM fits into this plan and depends on the goals you seek to achieve. These issues are discussed in Chapter 4, while the value of understanding climate related to BEM is reviewed in the next chapter.

Exercise: Calculate the zEPI and CO_2 Emissions

Q1: Calculate the zEPI for your building.

Using this equation:

$$zEPI = 57 \times (pEUI/EUI)$$

Baseline EUI = 49
pEUI = 42

Q2: How many pounds of CO_2 emission are saved with this zEPI? Reference an IGCC document for conversion factors.

A1/A2: zEPI and Carbon Emissions

Elaborating on the answer, if we have an office with a standard baseline EUI of, say, 49, and modify this baseline to propose a pEUI of 42, the zEPI equals 48.9, passing the code limit of 51. Running our zEPI score through the CO_2 emissions for our 86.5 MWh base office building, we first convert the energy for Miami, Florida using table 602.1.2.1, taking 2.97 and multiplying the two totals for the base and proposed building. The base building emits 256.9 lb of CO_2. The proposed design MWh total is 76 and emits 225.72 lb of CO_2. Therefore, the proposed design emissions total is less than the CO_2 emissions of the base design, saving 31.18 lb of CO_2 with a zEPI of 48.9.

If your math is right, the example passes the modeled performance pathway requirements of the IGCC. The concept behind the zEPI is a rating scale where 0 would be 100 percent energy savings (or an energy consumption of net-zero source energy) and 51 is a 10 percent energy saving against the standard reference design. A building that is 100 on the zEPI represents the 2003 CBECS baseline average for its location and building type. Using the linear logic embedded in the zEPI scale building is essential for complying with the 2030 challenge; our current scenario of 12 percent CO_2 reduction falls a bit short of the 70 percent expected. We would need to achieve a zEPI of 20 in the year 2020 to meet the 2030 goal of achieving an 80 percent CO_2 emission reduction.

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3 Climate Opportunity

Assessing design opportunities provided by the local climate is necessary for any project. Adequately understanding how a building is sited, its rural or urban context, its orientation to the sun, and the annual temperature, humidity, wind, and rainfall all help define possible passive and active sustainable design strategies.

Our planet is a complex ecosystem made up of different combinations of weather. Translating global design approaches to your location requires understanding the features of climate. To help make sense of it all, the world map originated by Koppen-Greider[1] shows climate classifications based on geographic location, temperature, and precipitation. Used by atmospheric scientists, it has been and continues to be a valuable way of examining the world's climate.

In the U.S., climate zones, based upon ranges of temperature and humidity, are used as prescriptive and performative energy compliance for residential[2] and commercial buildings. Within these zones exist climate-responsive vernacular architecture. Often, these early climate-adapted buildings inspire today's place-based design approaches to materiality, form, daylight, and ventilation of buildings.

Within the U.S., each climate zone is classified depending on its weather, latitude, and elevation, simplified as subarctic, very cold, cold, cool, mixed, warm, hot, and very hot. Across the zones there exists variation as to whether it is a dry, humid, or marine location.

Building science lies at the heart of defining the climate zones shown in Figure 3.1 and their related thermal performance expectations for residential and commercial buildings. Understanding the relationship between climate and building forms the forefront of high-performance green building.

Alternatively, the quantification of our climate has had the negative effect of dehumanizing it instead of allowing us to understand climate intuitively. Only understanding climate by the numbers could lead to builders, architects, and engineers blindly following code pathways and ignoring specific micro- and macroclimatic effects. While codes and standards exist to protect the quality of the interior environment from unhealthy and unwanted conditions, by providing mechanical

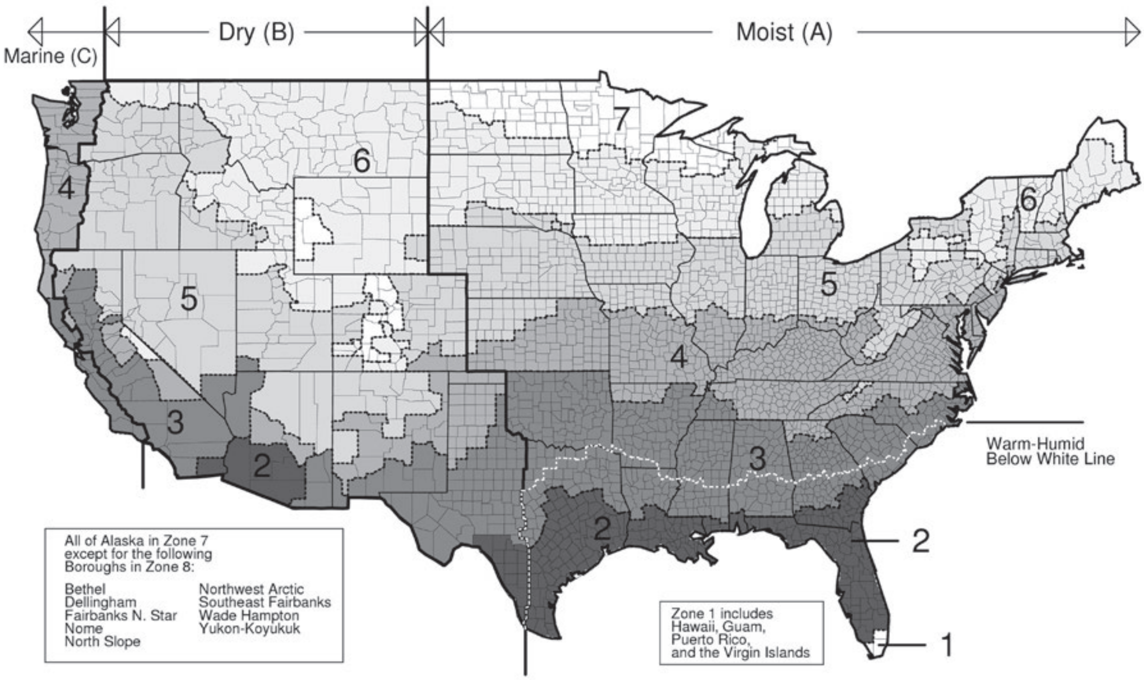


Figure 3.1 International Energy Conservation Code's map of U.S. climate zones. Copyright © 2015 by International Code Council, Inc.

means to create livable building conditions it is possible to miss the climate opportunities available for achieving greater building performance.

Two ways to categorize buildings accordingly would be either climate-rejecting or climate-adapted. The books *The Design of Energy-Responsive Commercial Buildings* by the Solar Energy Research Institute[3] and Ken Yeang's *Ecodesign*[4] examine two different ways that commercial buildings are energy responsive and discuss the two extremes of how a building positions itself within its climate. A climate-rejecting building is one that primarily relies on active systems—mechanical means—to heat, cool, and ventilate the building. The climate-adapted building alternatively incorporates as many passive systems as possible to help heat, cool, and ventilate the building. Today we might call this bioclimatic or passive solar design, one that meets the human need for a comfortable interior environment tailored to the specific climate. The climate-adapted approach utilizes the available sun, wind, water, and earth to provide heating, cooling, and ventilation.

The goal of both approaches is to create a comfortable interior thermal environment. It is not an either/or situation, but more of a both/and approach to maximizing the energy responsiveness of our designs. To achieve the greatest operational efficiency within a building, mechanical systems may be the best and ideal solution. However, maximizing architecture's role in conserving energy requires designing architectural climatic adaptions that can reduce the building's reliance on purely mechanical solutions, creating a hybrid between the climate-rejecting and the climate-adapted building. Creating the ideal interior environment

therefore requires us to understand more about how our building design behaves within the local climate. This chapter describes using BEM to gain knowledge about the weather, macro- and microclimates, and how to understand and analyze the climate when making design decisions.

Weather Files

Software can present you with an immense amount of information about your project. There exists a wealth of data related to weather that helps us understand the larger, macro-scale picture of a climate, including information related to the outside season temperature (both dry and wet bulb), wind direction and speed, humidity, sky cover, and radiation. However, the program you might be using is not omniscient; it is merely providing data from a weather file based on your specific geographic location.

Making an informed choice about which weather file to use is important. Studies have evaluated the impact of using different weather data to evaluate aspects of the same building. The most sensitive elements for a building's optimal energy performance can change based on the weather file used. Understanding the composition and creation of weather information is important, and the U.S. DOE provides guidance on where to locate weather files and how to use them.[5] Research shows that choosing the right weather file is important to a building's overall performance,[6] since we are designing buildings for future weather trends, not past ones.

Typical Meteorological Year

A BEM uses weather files to describe the climatic context for our building. Weather files represent a historic picture of climate conditions for a specific location and are called Typical Meteorological Year (TMY) files. Recent freely available files are TMY3, created to document an average year based on a span from 1991–2005.[7] Other TMY files, such as TMY7 or TMY15, use different timeframes for the data comprising the file and are either sourced from a third party or created manually. The weather file is a multi-year aggregation of precipitation, temperatures, radiation, and other weather data specifically meant for BEM. Since TMY files aggregate a range of years, they do not capture extreme conditions—for example, the seven feet of snow or the week of sub-zero temperatures. However, TMY files are valuable because they have been validated, cleaned up, and contain the most accurate usable data. TMY files are common, but are not the only source of weather information.

The TMY is the most widely accepted weather file for BEM, though several BEM tools also construct their own weather data. Other sources include

program-specific data, third-party files, California Title 24 weather files, and real-time weather data. EnergyPlus (E+) has translated TMY files into an E+ Weather file (EPW)[8] using a variety of information sources. Autodesk collects weather data for use in Green Building Studio and allows it to be exported to E+ and other platforms. The National Weather Service (NWS) collects information from 4,000 stations across the U.S. and can be parsed by any third party or used as real-time information. For California Title 24, weather files are specific to the climate zones defined for the state and read by BEM programs specific to Title 24 compliance. Information on weather data is highly diverse and takes some patience and focus, and is the specialty of some consultants and third parties.[9] TMY files are good enough in many cases to simulate typical building operations using BEM; however, they do not capture all the different weather conditions a building might experience and are insufficient for evaluating future climates. It is therefore important to evaluate the file to ensure that the data are valid for the specific use intended.

Extreme Meteorological Year (XMY)

One of the godfathers of BEM, Drury B. Crawley, proposed the use of the eXtreme Metrological Year (XMY).[10] XMY data are not necessarily a standard downloadable file common for use in BEM. Created by knowledgeable climate scientists, engineers, or energy modelers, XMYs are used for specific research or experiments. Making such a file requires parsing through weather data and identifying extreme patterns and their variability over a variable number of years. The compiled data represents 8,760 hours per year of weather for however many years are included. XMYs often use statistical forecasting to produce changes in the mean and variance for different variables over the course of a year or period of change. Once the XMY file is ready, a BEM simulates the effects of extreme weather conditions on a building's performance.

While XMY files are still not widespread, Drury and others[11] recommend the use of multiple weather files to capture the range of a building's performance. One suggestion is using three different climate files: one typical, one colder, and one hotter. There may never be an exact way of accurately predicting a building's energy performance, but this variation helps us understand the range possible within these climates. Using multiple weather files can also demonstrate the potential long-term variability that exists for building operations.

Actual Meteorological Year

The actual weather patterns of a specific climate are contained in an Actual Meteorological Year (AMY) weather file. Here, one takes the weather data from local weather stations and uses the information directly to create a simulated

environment that tests a building's energy performance in BEM. This can be most useful if you seek to understand how a design would have performed recently in a specific location, since it captures the actual local weather patterns, whereas the TMY and XMY files provide extrapolations of the weather. The disadvantage of using AMY weather data is that such files can provide inaccurate data in cases where there was a local weather anomaly, or if a recent winter or summer was particularly mild or extreme (though climate research shows that these anomalies are rapidly becoming the norm). In either case, the building design and means to heat, cool, and ventilate may not be adequate for the extreme conditions or even for longer periods of typical weather patterns. Another common use of AMY files is calibrating the energy model with actual operational data after the building has been completed.

Customizing TMY

The weather is the primary consideration for identifying passive strategies in architectural design, since it allows the architect to define different passive opportunities. A best practice is to design based on multiple climate scenarios as well as for expected reasonable extreme conditions.

Experts in BEM know that using weather files requires some customizing. Many TMY files have some fixes or errors in the weather set. TMY files are constructed through a standard methodology,[12] and updates of the files occur regularly.[13] Additionally, California has specific model code compliance weather files for different jurisdictions. Canada allows design teams to develop the climate zone through bin analysis to determine the data that best fits the climate they are designing around, whether that climate belongs to today or 100 years from now. Depending on the intent or climate model, energy modelers can modify the TMY files to be predictive and to fix raw data errors, effectively making a more appropriate way to simulate the building design and demonstrate compliance where necessary.

Weather Data Use

BEM's use of weather data helps designers, architects, and engineers simulate and understand the specific climate conditions for building design. That said, simulated energy savings and peak demand reduction by energy conservation measures using the TMY3 weather data can be significantly under- or overestimated,[14] and the choice of weather files will affect the building's total energy performance. BEM, however, has the best potential to aid designers in reducing energy consumption, though it cannot itself accurately predict an actual building's performance. BEM helps us make the best choices, not find a perfect answer.

Next, we show how leveraging macro-scale climate information contained in weather files helps to identify design opportunities related to temperature, humidity, wind, precipitation, earth, and sun. Following this, using BEM can aid in evaluating micro-scale site-specific weather conditions. The scalar climate issues aid in the identification of climate analysis and in considering the questions necessary in building design.

Energy and Climate

An understanding of a climate at the macro- and micro-scale is vital in prioritizing the possible passive energy approaches for design. A building's specific location has the greatest influence on energy consumption, and shaping the building form to maximize architecture's role in optimizing all the passive possibilities depends on the external climatic conditions and the local weather. The building's enclosure mitigates the external forces to create internal climates deemed acceptable by the occupants. In doing so, the building design and its relationship to the climate can reduce the building's overall consumption of energy, creating internal conditions through passive and mechanical systems for heating and cooling.

Where a building is located on our planet influences its design. Climate conditions and seasons vary by location, as do the people who live there. From a range of different global climates—tropical, desert, temperate, cool, and polar—the weather varies, as does the location of the sun. Near the equator the sun is overhead all of the time, whereas near the poles the sun can be absent for months on end. Additionally, social and physical preferences vary as well; not everyone on the planet may prefer the thermal comfort zone in the same way, or experience it homogeneously. These global issues of climate, location, and perception of the climate significantly affect the building design for many of the passive strategies we employ.

To affect energy consumption within the building, we need to understand the basic principles of energy itself. Basic building physics comes from several laws of thermodynamics.[15] The first law of thermodynamics states that energy can be neither created nor destroyed; therefore, all the energy that can ever be already exists within the universe. This is also known as the law of conservation of energy, which states that the energy within the universe is always the same. While overall energy remains constant, energy can change forms. The second law of thermodynamics states that closed systems move to disorder over time; this is also known as the law of entropy. Entropy drives the behavior of heat flow from hot to cold. Bodies also move energy from hot to cold in the form of heat.

Therefore, the goal of an energy-efficient approach to a climate would be to capitalize on the available free energy by passively dealing with the thermal conditions of the site and climate. This includes using the sun's energy to heat, the wind to ventilate and remove heat for cooling, water to add humidity, and the earth

and materials to store or remove heat. Since temperature and humidity control thermal comfort, passive solar and bioclimatic design involves levering thermodynamic principles to conserve the energy available locally, rather than relying on importing energy from fossil-fuel sources.

The key to successful integration of this free energy is designing for how we experience comfort. Since our buildings should adjust the external climate conditions to an interior climate that is comfortable for the majority of people most of the time, how our bodies experience this interior climate requires description. What the body senses is the air temperature (dry bulb) related to the amount of moisture in the air, known as relative humidity (RH). The more moisture in the air, the higher the wet bulb temperature; this means that the apparent temperature feels warmer when the RH is higher. Wind, on the other hand, causes the evaporation of sweat and moisture from our bodies, making us feel cooler. When the air is cold, its movement can cause wind chill. In each instance, the temperature, measured via a dry bulb, is the same—it is the amount of moisture in the air or the velocity of the wind that makes it feel different.

By further using energy-modeling programs we can define project criteria, such as temperature and humidity levels, important to prioritizing design goals. The weather within any climate zone has natural variation depending on the time of day, the season, and the microclimate conditions. Analyzing and understanding this variability, quantified within the weather data used in the BEM analysis, is part of prioritizing the design approach. Evaluating these macroclimatic variables is important for architectural design to tailor a building to the local temperature, humidity, wind, precipitation, earth, and sun.

Understanding the Macroclimate

Temperature

We know from experience that outside temperature varies from hot to cold and cold to hot, with a wide range in between. Many architecture students have likely had to calculate the heating and cooling degree-days (HDD and CDD) for their building's location. I certainly didn't think much of this as a professional until I started working on zero-energy buildings and needed to define the exact role of passive opportunities for the climate in which the building was located. Since climates vary depending on location, quantifying the HDD and CDD helps understand the amount of heating or cooling needed in your location.

Locations vary in their need for cooling or heating. For example, if you live in Minneapolis, you will need more heating and not much cooling each year. Alternatively, if you were sitting on the beach in Miami or southern California, heating is not something you are thinking about. If you fall somewhere in between, you likely require a bit of both heating or cooling to maintain a decent level of

personal comfort. Identifying the primary mode of maintaining human comfort precedes identifying any specific climate opportunities.

If the outside conditions and building use allow, passive ventilation might be possible for keeping interior temperatures within the comfort zone. For instance, using the temperature per month provided by the weather file and presented as average temperature ranges (Figure 3.2, left) shows there are limited hours for natural ventilation opportunities during the year, reducing but not eliminating the need for cooling. Comparing this with the weather data from another location (Figure 3.2, right) shows that natural ventilation might potentially eliminate the need for any cooling.

Mapping the summer temperatures per hour of the day can identify when during a season they exceed or meet desirable comfort levels. Over the course of a year, as shown in Figure 3.3, the BEM tool plots temperatures for each hour of

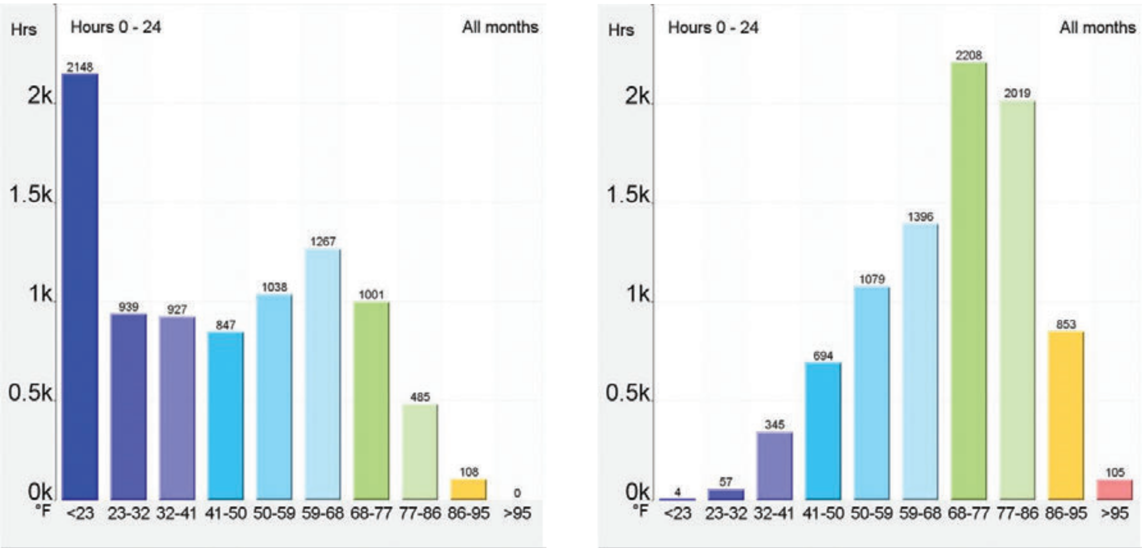


Figure 3.2 **Annual temperatures in Fargo, North Dakota (left) and Houston, Texas (right). Images courtesy of Integrated Environmental Solutions Limited.**

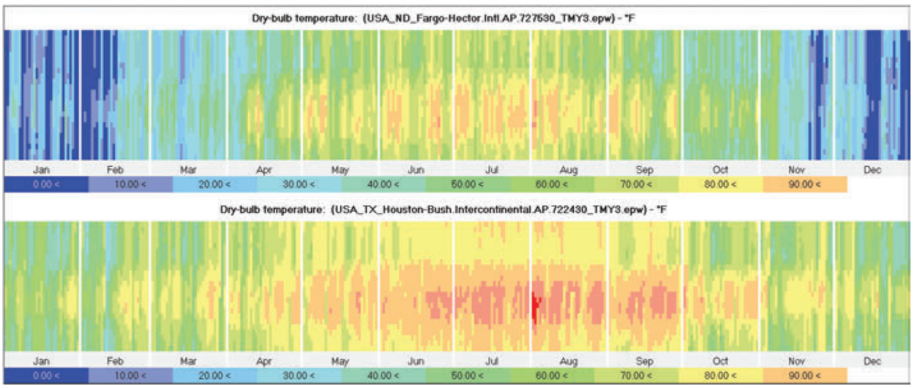


Figure 3.3 **Hourly dry-bulb temperatures in Fargo, North Dakota (top) and Houston, Texas (bottom). Images courtesy of Integrated Environmental Solutions Limited.**

the day. This comparison of annual temperature shows us when ventilation (green colors) is a possibility. Temperature informs us when certain passive strategies might be pertinent, but the architectural design itself should weigh all climate data together before embarking on a specific solution.

Humidity

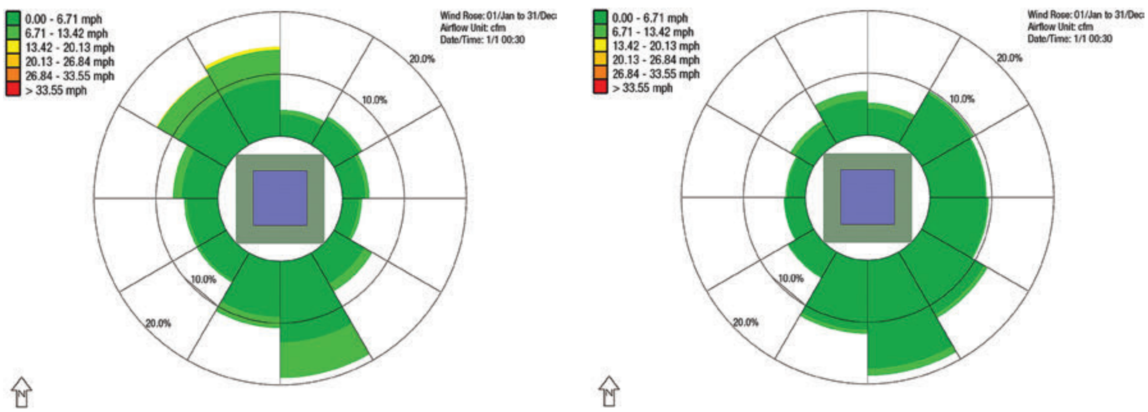
Humidity is another factor, alongside temperature, that influences our comfort level. Most importantly, maintaining humidity within specific levels in an interior environment protects our health. Conditions that are too dry or too humid can cause respiratory issues. Since humidity is related to climate, the humidity inside a building therefore needs to fall within a healthy range, aided by mechanical systems that either add or remove humidity to or from the air. While the energy burden is minimal for many types of facilities, it does influence the opportunities within some climate zones.

Specifically, within mixed climates where both dry and humid conditions exist during some seasons, designing passive systems can be a challenge. For instance, when temperature conditions might be ideal for natural ventilation, the humidity might not. Alternatively, in hot-humid climates, removing humidity from the air can be a full-time job for a mechanical system.

Wind

Wind roses report a location's wind patterns at a macro level. These diagrams show us from which direction and at what speed the prevailing winds come. Comparing the same two locations for which we gathered temperature in Figure 3.2, one can see that at the first location seasonal wind speeds are much greater than at the second (Figure 3.4). However, the second location has a larger percentage of time

Figure 3.4
Seasonal wind roses for Fargo, North Dakota (left) and Houston, Texas (right). Images courtesy of Integrated Environmental Solutions Limited.



when the winds come from the southeast, making ventilation again more feasible due to the wind's lower speed and longer duration.

The goal of evaluating wind roses is to identify the desirable periods for wind penetration versus the periods in which the building requires protection from the wind. Climate consultant software can animate wind-rose patterns throughout the year. While this is fascinating to watch, it more importantly shows a designer how prevailing winds move and fluctuate for a specific climate. Other BEM tools also show wind patterns that designers can use for climate analysis.

The caveat is that these opportunities exist at the macro level. Wind patterns vary at ground level and at different locations in the terrain. Since the weather station might be at the airport or on top of a tall building, the specific application of wind data needs to be assessed locally at the micro-scale of the building site. Working with local experts or doing your own measurements can help you understand the site-specific wind conditions.

Precipitation

Snow, rain, and ice are important design factors, and they drive structural calculations for climates where heavy snow can be expected. Buildings are detailed specifically to keep water out and to resist damage caused by freezing. These items at first may not appear to offer any passive heating or cooling opportunities for energy savings; however, some BEM programs can calculate precipitation to determine water conservation strategies within and outside of the building. Precipitation data is included in the weather files and is an important aspect of an environmentally sustainable design approach.

Earth

Though perhaps not a specific weather element, the earth can still play a valuable role in how our building performs. Using the ground beneath our feet has the potential to increase the climate-specificity of our designs. Incorporating the earth through coupled heating or cooling systems such as geothermal, ground-source heat pump, earth tube, and labyrinth systems takes advantage of the earth's constant temperature to passively maintain interior temperatures. Climate data logging the earth's ground temperature is available in or can be derived from available weather files. While using a BEM to model these complex earth-coupled systems is not a typical BEM exercise, the potential for considering this information and the resulting climate opportunities does exist.

Additionally, the earth's shape or landform exposes our building to the sun in different ways. As with a building's orientation, which slope we choose to situate our building on will affect how the wind and sun interact with it: for

example, southward-facing slopes maximize a building's exposure to the sun. Whether winds go up the hill or down the hill will aid in determining the potential and shape of our building for ventilation.

BEM tools support our understanding of how the building interacts with the ground temperature for passive systems and helps determine how far we wish to locate our building in or above the earth. Additionally, the landform and our building's location on a site affect how the building interacts with other climatic elements.

Sun

Along with air temperature, the sun determines many of the passive solar design opportunities within the specific climate zone. Together, temperature and sun—more specifically, solar radiation—have the biggest impact on passive strategies. Understanding how to design for the sun is the subject of numerous books and publications on passive solar design. Since this book is about the use of BEM in architectural design, the specific focus is on what the software can inform you of and how one might design based on this information.

Many three-dimensional modeling programs show us what a building looks like in relation to the sun. Called a sun-system, this feature allows the user to position the sun based on a specific location, along with inputting the year, month, day, and time of choice. From simple to complex sun systems, important to how we may choose to design our building is the ability to see where the sun is.

As is well known, the sun moves throughout the day from the east to the west and changes its height in the sky, illustrated in Figure 3.5. These are two key measurable attributes known as the sun's azimuth and altitude. The sun's azimuth is the measure of its location on a horizontal plane at an angle where north is 0, east is 90, south is 180, west is 270, and north is again 360 degrees. The solar altitude angle then comprises the angle of this horizontal plane to the sun's position in the sky, ranging from 0 to a zenith of 90 degrees. Using these two metrics for your specific latitude north or south of the equator can identify the sun's location throughout the day and over the course of the year. Once located, graphics or regulating lines representing the sun's parallel rays help identify how the building and sun interact at a specific time or throughout a season.

Using this information in design with BEM identifies situations and periods for which the sun is required. Commonly, identifying the two extremes—the winter and summer equinoxes—helps us see the narrowest and largest ranges of the sun's movement in the sky. This can then help us identify when we can use the sun to passively heat our building. Bracketing the months where we want our design to allow sun penetration into the building—for example, in climate zones 5A and 4A this tends to be between September and April—would enable us to

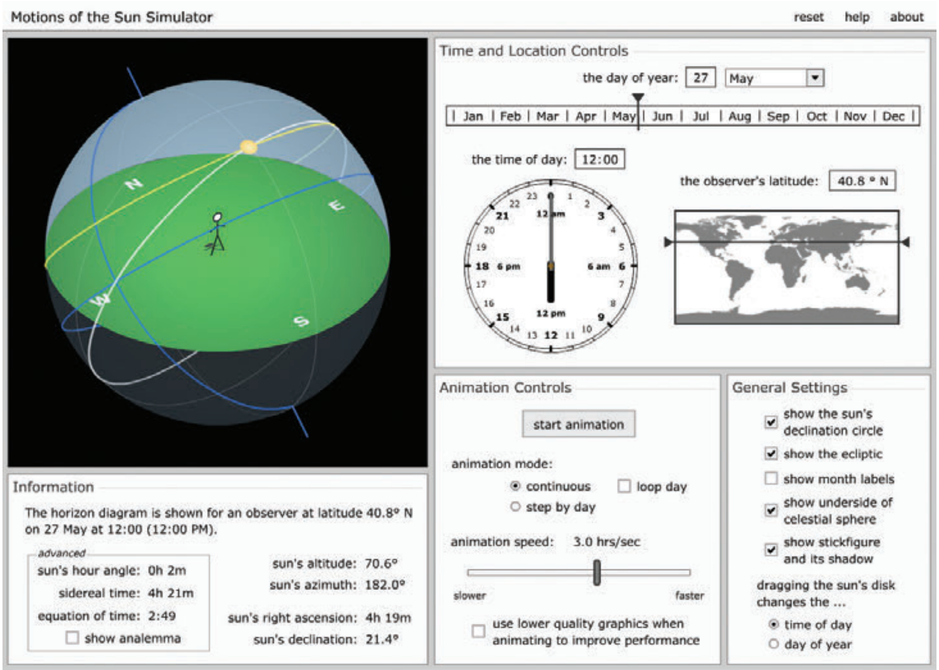


Figure 3.5 **Sun simulation website from the University of Nebraska-Lincoln Astronomy Department: http://astro.unl.edu/classaction/animations/coordsmotion/sunmotions.html.**

design openings and apertures and locate spaces. Next would be the omission of the sun during periods when it would introduce heat when cooling is predominant. The drive to avoid this excess radiation typically occurs during the summer cooling months. Again, bracketing the months and identifying this period will help designers design shading devices. Framing the problem properly helps identify the specific range in which we can design using the sun, along with how BEM is beneficial.

Weighing the temperature, humidity, and solar radiation values related to your climate location is the first step in a BEM analysis for maximizing passive solar climate-adapted buildings. Whether your location is hot or cold, dry or moist, or has a lot or a little sun, the availability of these naturally occurring phenomena establishes a beginning for design. Without considering climate early, we default to over-reliance on mechanical systems to produce acceptable environments within our building. Furthering the responsiveness of the building to climate is our evaluation of the microclimate at the building site.

Microclimate Opportunities

By using BEM tools we can define project criteria important to prioritizing design goals specific to our building site by evaluating the microclimate conditions. Here we can utilize some other functions of BEM tools, along with Computational Fluid Dynamics (CFD). One parameter is the context of the building site, whether

urban, rural, or somewhere in between. The existing microclimate should influence where exactly we locate our building. In addition, once there, how will our building affect this microclimate?

To understand the building and microclimate reciprocity, using BEM and CFD can give us information about the available solar radiation, heat island, ventilation, and contextual shading, or reflectivity of nearby buildings. Solar radiation analysis tells us the amount of the sun's energy that strikes a surface. Within a specific site it is possible to utilize weather data and geospatial modeling to identify the range of radiation that falls on a site, whether a greenfield or an urban context. Using CFD analysis, one can measure, visualize, and understand temperature along with the speed and direction of wind across the landscape, including the effect of adjacent buildings and our building design's effect on the ground-level wind velocity.

Heat Islands

Yes, asphalt and a paved urban environment make our cities hotter. This is typically called the urban heat island effect, in which the buildings and materials create their own microclimate, typically warmer than would otherwise occur naturally. While we may all intuitively know that sitting down for a picnic under a shady tree in the summer is going to be cooler than walking down a paved concrete street with the hot sun beating down, it is possible to actually measure and visualize this effect to aid our design decisions.

Research shows that the heat island of a metropolitan area with one million people can be 1–3 °C warmer than the suburban surroundings. Overnight, the effect can be even higher, by as much as 12 °C due to the thermal mass of all the people and buildings.[16] These effects exacerbate peak energy demand, air-conditioning costs, air pollution, and our health. Hot urban environments can trap air pollution, irritating respiratory issues and causing vulnerable populations to be at higher risks for illness and death.[17]

Therefore, addressing the heat islands within urban areas is one key benefit of using BEM tools and CFD analysis to deal with air movement, reduce solar radiation, and situate our buildings within this context in the best way to promote a healthy urban environment. As a case in point, the location of green spaces and vegetation also has a positive impact on wind flows and temperature, as shown in Figure 3.6.

Ventilation

Design for effective natural ventilation requires understanding of how the building is sited in its context, specifically with regard to the wind's direction and velocity. Wind movement through a site can induce convection and

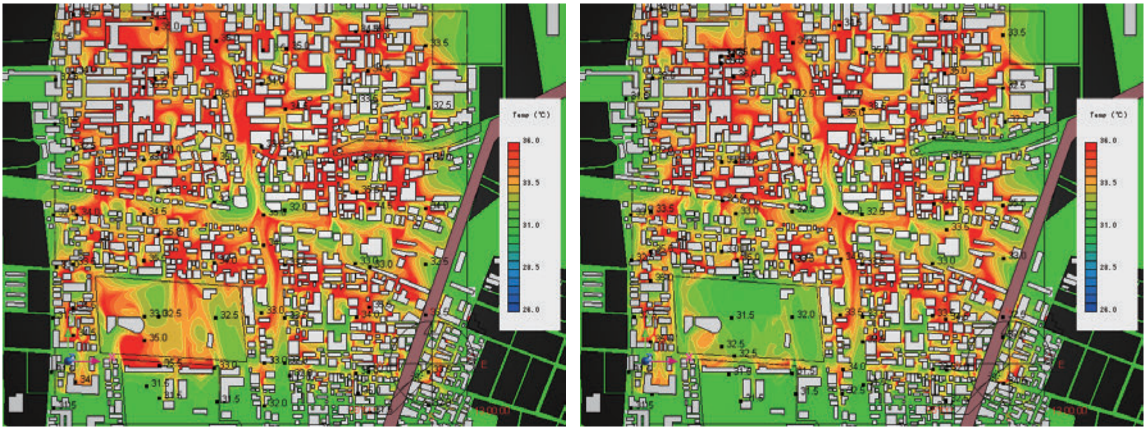


Figure 3.6 **CFD thermal analysis of ground-level temperatures, comparing the temperature difference between a parking lot (left) versus a green space (right). In both images the parking lot/green space is located in the bottom left boundary. Images courtesy of Cradle CFD.**

evaporation, and these aspects affect temperature by either displacing it or adding moisture.

A local understanding of wind flow is important, as the denser and more vegetated an urban context, the more turbulent the flow of wind becomes. Prevailing winds are altered as they move across the landscape, through vegetation and over and around buildings. Poorly considering the building's relationship can produce wind conditions at street level fit for neither man nor beast.

Situating the building to take advantage of wind means understanding where the wind will go and how features and landforms affect it. Hills can speed up wind velocity. Adjacent buildings can funnel or direct wind in specific directions. To evaluate all these aspects, some BEM tools or CFD analysis may be necessary. Simulations of wind direction and velocities external and internal to the building design can help properly form and shape the building to maximize architecture for natural ventilation.

Daylighting and Shading

Another issue possible to evaluate using BEM is the building's site context for daylighting. Adjacent buildings can shade or reflect light on to the areas where we might locate our buildings. If we wish to maximize daylighting, then understanding how a context might shade portions of a site is important. In addition, light reflected from adjacent buildings could increase heat gains and the amount of diffuse light factored into daylighting analysis.

Modeling the context of a specific site and completing annual shading analysis will modify both the amount of sun available for heating and the nature of daylighting design possibilities. Different types of urban and rural contexts create uniquely dynamic conditions: For instance, during the winter very little exposure of a building to sunlight in a dense urban environment will make the street cold and undesirable.

Research by authors on the urban form is mostly based on Ralph Knowles's solar envelope research from USC. Since the 1980s, Knowles has produced a range of representations of urban form based on its relationship to the sun and the shadows produced. The resulting building forms respond to the sun in a variety of ways to allow penetration and access within and around their particular site boundaries. As Knowles reflects on the solar envelope, he says that the "interstitium allows architects to conceive a kinetic landscape driven by the rhythms of nature."[18]

Vegetation

Vegetation has several useful purposes. Plants can help shade the building during peak cooling periods to reduce the amount of solar radiation striking the building surface and can also shield the building from prevailing winds during the winter to protect it from cold. Vegetation can further shade the ground surface, cooling the air and its flow for ventilation.

While researchers have studied the effects of trees much more than other issues relating to the urban form,[19] they are not always beneficial. Planting undesirable trees in the wrong locations can have a negative effect, blocking light and prohibiting ventilation. Planting a tree directly south of a home can actually cause a net increase in annual energy costs.

The benefits of using trees to save energy rely on the cooling effects of tree shade and evapotranspiration. Placing deciduous trees on the west or southwest side of a building in regions with hot summers and cold winters provides shade in the summer and allows solar radiation penetration for passive heating during the winter. Trees with high levels of evapotranspiration can also add small amounts of moisture to dry breezes.

Visualizing Climate for Design

Armed with a wealth of information about a specific macroclimate, we can visualize this data in relation to our building, supporting an analysis of how a building might perform. Weather analysis tools help in visualizing the information as shown above, and provide a way to analyze the results to identify design strategies.

One robust analysis tool available for furthering this is UCLA's Climate Consultant software. Using this tool, designers can examine weather data and assess a building's relationship to climate. The software helps to identify the specific design strategies most appropriate based on the climate. For example, Table 3.7, recreated from the Climate Consultant software, identifies the number of hours for which a building is passively at the comfort level and then the number of hours

Table 3.7 **Summary of annual bioclimatic design strategies for two hot climates.**

	Miami		*Phoenix*	
	1A		*2B*	
Design Strategies: January–December	*%*	*Hours*	*%*	*Hours*
1. Comfort	14.3	1,252	16.6	1,451
2. Sun shading of windows	27.2	2,385	25.6	2,241
3. High thermal mass	2.9	257	–	–
4. High thermal mass night flushed	–	–	–	–
5. Direct evaporate cooling	–	–	–	–
6. Two-stage evaporate cooling	–	–	29.3	2,570
7. Natural ventilation cooling	3.1	273	7.0	611
8. Fan forced ventilation cooling	–	–	–	–
9. Internal heat gain	8.0	703	22.3	1,957
10. Passive solar direct gain low mass	–	–	–	–
11. Passive solar direct gain high mass	3.8	334	12.2	1,071
12. Wind protection of outdoor spaces	–	–	–	–
13. Humidification only	–	–	–	–
14. Dehumidification only	16.3	1,427	0.5	43
15. Cooling, add dehumidification if needed	55.9	4,894	12.7	1,115
16. Heating add humidification if needed	1.6	139	14.6	1,280

for which other active and passive elements are required to maintain the level of comfort. Most noticeable between these two hot climates is the use of evaporative cooling versus the need for dehumidification, while the use of sun shading has an almost similar effect.

As has been shown, many BEM tools can visualize the climate. Of particular help can be a single chart showing the monthly temperature, radiation, and humidity fluctuations. Graphing this information together, as in Figure 3.8, helps to show when passive strategies will work in heating and cooling the building. For instance, Climate Consultant helps to visualize annual, monthly, and hourly averages of temperature and radiation alongside the comfort zone, making it easy to understand the months requiring cooling and heating. It can also aid us in visualizing the relationship between radiation and temperatures to determine at which points during the year thermal mass and night flush systems can assist the building's passive systems.

The graph from the weather file shows hourly information. Depending on the fidelity of the analysis required, teams could forecast the approximate times during the entire year that specific design elements could help heat and cool the building. This information is helpful within the macro-scale to identify what may or may not be appropriate. However, after this stage, it is important to look more closely at the issues of immediate concern at the building site.

While there are likely an infinite number of examples of how to incorporate climate outputs into a design model, several are discussed here. Using features

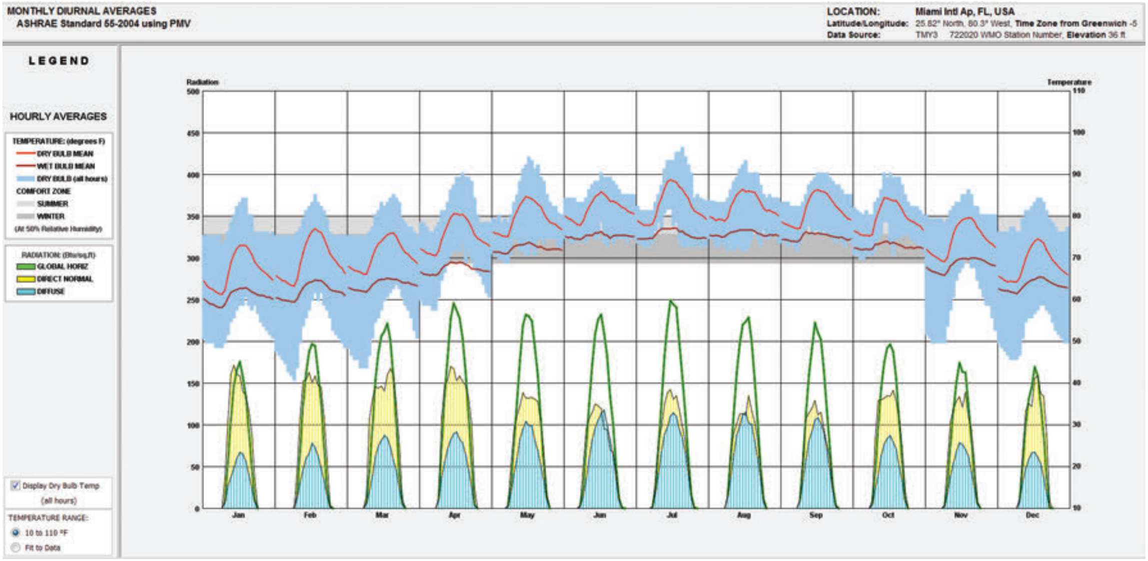


Figure 3.8
Composite output of radiation and temperature from Climate Consultant.

of different BEM tools allows architects to visualize the sun's radiation and to see the sun's path and the building in the same design space. An overlay of the wind rose into the design model visualizes wind data for each hour, day, and/or month of the year. These features help an architect make basic design decisions related to climate. How we examine and interpret various aspects of climate helps the building design. Using these along with a complete BEM can also relate specific design decisions with energy savings.

Sun Radiation

The presence or absence of the sun has a large impact on a building's heating and cooling loads. The preeminent source on designing for solar radiation is Edward Mazria's *The Passive Solar Energy Book* in which he outlines ways of designing buildings to relate to site, climate, material use, and the sun. The methods and data presented by Mazria are now fundamentals included in many other books and software. Most important are the passive solar systems clearly outlined as approaches to heating a building passively. The book provides information on the thermal impact of direct, indirect, and isolated gain systems, as well as 27 patterns of design that embrace the sun.[20] Following these patterns and use of passive thermal heating increases the architect's capacity to design with the sun's energy.

Visualizing the information and collecting the data Mazria demonstrated and presented is easy to do today using BEM. Advances in computation make it easy to calculate HDDs or CDDs for a local climate, normalized as part of ASHRAE Standard 90.1 and based on climate zones. Along with temperature and

humidity, the sun's radiation values are part of the weather data we download and use in BEM.

The sun's radiation reaches the earth and our building in three primary forms: direct radiation, diffuse radiation, and reflected radiation. Once radiation reaches the building's surface it is reflected, absorbed, or transmitted by the material composition of what it strikes. The property of the material will dictate how much is reflected and in what way, what is absorbed, and then how it is transmitted through the material. Once absorbed, the radiation is transferred into energy as heat. The material properties that inform how radiation behaves once it is absorbed and transmitted are beyond the scope of this book, though for those interested we recommend Steven Szokolay's *Introduction to Architectural Science: The Basis of Sustainable Design* (third edition).[21]

Visualizing the total amount of radiation on a building over the course of the day for the climate selected, as shown in Figure 3.9, is one place to start, since knowing where the majority of radiation strikes helps to prioritize the passive solar strategies. Since this precedes the building design in most cases, completing more radiation analysis is possible once a definition of the building form reaches a schematic level.

Certain software tools can help us see how much radiation strikes the surface of a building. Vasari, IESVE, and DIVA are those familiar to us; each can

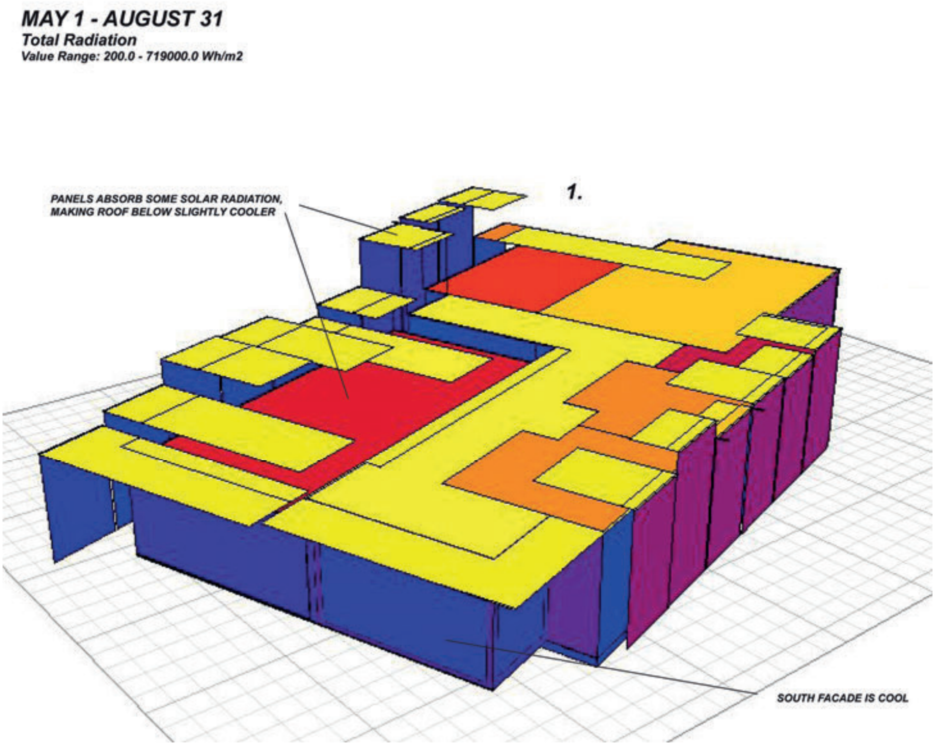


Figure 3.9 **Solar radiation levels during summer months on a small commercial building. Courtesy of Michael Harpster. Timothy L. Hemsath "Energy Modeling in Conceptual Design" Fig 7.2 from *Building Information Modeling: BIM in Current and Future Practice* by Karen Kensek, Douglas Noble. Copyright © 2014 John Wiley & Sons, Inc.**

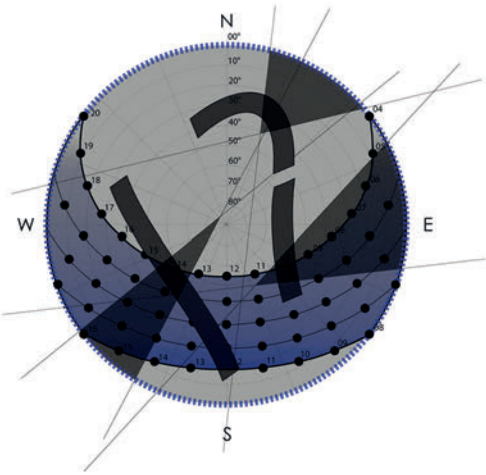
show the amount of radiation that strikes a single surface or multiple surfaces. To view these data, first define the period, whether it be a single hour, day, week, month, or year, then select the surfaces to study and the geometry to include. It is vital to consider the amount of detail you wish to include, as more complex geometries and larger surface areas require more time and computational power to analyze. It is often helpful to select a part rather than the whole.

Sun Path

BEM tools and design modeling software help by visualizing the sun path's azimuth and altitude. Seeing the sun's location in relation to our building design helps us make key decisions about the site, building mass, and shape (Figure 3.10). Knowing which parts of a building design lie in sun and shadow and how these patterns change over the course of the year helps us evaluate whether they will perform as intended in our design.

Site issues might involve shadows from adjacent buildings or shadows cast by the building on adjacent neighbors. Since these issues are often faced by designers, mapping or animating the sun path and resulting shadows over the course of a day, month, or year helps to show the impact of a building's shadow on a site. Depending on the software, a sun study produced in a short movie by animating the sun over a period of time may help show how the shadows change.

Understanding the sun's effect on our building massing aids designers in determining shading, as well as in locating courtyards or roof gardens. Since different programs and spaces might be active at specific times of the day, designers can evaluate whether an outdoor space in their design would receive



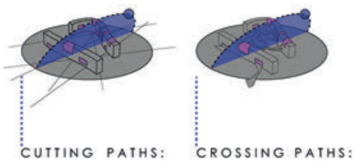


Figure 3.10 **Design operations based on sun location for light and shadow. Courtesy UNL student Mallory Lane.**

direct light or be in shadow, as well as judge the desirability of these spaces depending on their use and function. Shading devices for these spaces can be assessed by visualizing the sun and shadows created; for instance, if an outdoor playground is meant to be occupied during the late afternoon, shading devices to protect the children could be placed based on where the shadows would fall during the time of use.

Wind Direction

Incorporating a wind rose into the design model or drawings will show how the building can be oriented in relation to prevailing winds (Figure 3.11). Depending on the context of the building site, winds can be captured for natural ventilation, helping to passively cool the building. Locating operable windows on specific building façades in the path of desirable winds can allow for cross-ventilation. If the site is more complex in relation to adjacent buildings, the wind rose can help show where obstructions block winds from allowing effective natural ventilation. Of course, not all winds are desirable: high-velocity wind can be a problem, and we have

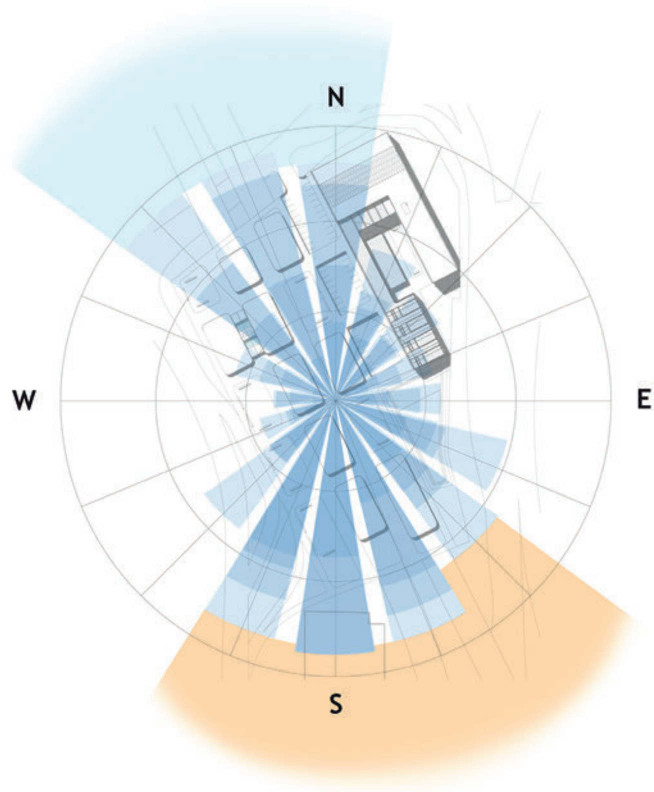


Figure 3.11
Site plan of building design with annual wind rose showing prevailing winds during summer and winter. Courtesy of UNL student Tyler Howell.

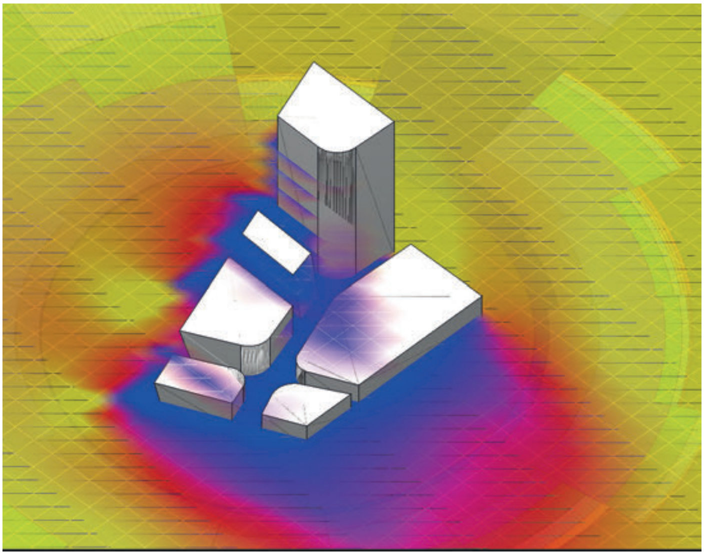


Figure 3.12 **CFD model of urban context and wind velocity. From Autodesk Vasari.**

all experienced the wind tunnel where winds are funneled down to the ground and concentrated where we are walking. While it is possible to shape buildings or create massing conditions that reduce the flow of wind, a wind rose alone might not be entirely capable of showing these effects.

Instead, utilizing CFD analysis is a complex alternative. While not specifically part of BEM, using CFD analysis alongside energy simulation helps to show how air movement occurs in, around, and through a building (Figure 3.12). Various windflow modeling tools from Cradle and IES to Autodesk are available to aid in evaluating issues related to wind conditions. The challenge, much like a robust BEM model, is verifying whether the information generated is usable for the situation. Experts and specialists in this area are often necessary to adequately model airflow. While natural ventilation is not an area of expertise in this book, others have published guides on designing spaces for natural ventilation.[22]

Climate Analysis

A robust climate analysis and inventory of the local site conditions and their potential effects on our design decisions is a good beginning to the design of climate-adapted architecture. A fruitful outcome is to increase the energy savings through the incorporation of passive systems designed as integral building elements. An important part of climate analysis is defining the comfort model.

ASHRAE 55 has several approaches to framing interior environmental conditions to understand the effects of exterior climate conditions. Since the goal of our building is to create comfortable interior environments for people,

the comfort model shows us, based on the specific standard, how many people it estimates would be comfortable in the set interior conditions. Additionally, the method used may bias the operational conditions assumed for the building, and choosing the right comfort model or evaluating several choices is important in understanding the complex behavior of the building within its climate.

Summarizing the weather's effect on human comfort comes from the climate data within a specific location and the comfort model used. Another particularly helpful graphical tool is the creation of the psychrometric chart[23] identifying where these strategies are effective to move temperature and humidity within the comfort zone.

Understanding the effects of the climatic variables related to the comfort of the interior environment lies at the heart of a hygrothermal and psychrometric analysis. One valuable tool for designers is the Center for the Built Environment's (CBE) comfort-prediction tools. By using ASHRAE Standard 55 as a guide, designers may find that a wider temperature band will provide adequate comfort and save a significant amount of energy.[24] In other cases, using this tool can assess the comfort zone for low-energy building design. Specific to ASHRAE Standard 55 is the adaptive comfort model for naturally conditioned buildings, which have no mechanical cooling system installed and no heating system in operation. The occupants within these buildings prefer a wider range of temperatures that reflect swings in the outdoor climate.[25]

The Chartered Institution of Building Services Engineers (CIBSE) recognizes that human comfort is key to accepting low-energy buildings that perform optimally.[26] Overheating of the interior environment in naturally ventilated buildings has become a key problem for building design. The need to reduce energy consumption and deal with global climate change often limits the options available for building a comfortable and low-energy building. Recent work present in European standards found the temperature that occupants find uncomfortable changes predictably with the outdoor conditions. These issues of naturally ventilated buildings inform the CIBSE guidance presented in a Technical Memorandum on the limits of thermal comfort.[27]

A few BIM tools offer adaptive comfort modeling capacity and output data related to how your building design meets the comfort model and expectations. To design a climate-adapted building there are several considerations to make relative to the building's design when considering both the macro- and microclimate. What should you ask of your climate analysis? What do you need to know about the particular climate to design a climate-adapted building?

Macroclimate

- In what climate is the building site located?
- What are the median, extreme highs and lows of temperature and humidity?

- When during the year are the cooling and heating periods?
- What period of the year is the temperature right for free cooling and natural ventilation?
- Where is the sun during the year in relation to our building?
- For what period of the year can the sun be used for heating?
- Where does the wind come from, for what duration, and at what speed?

Microclimate

- Does the existing vegetation and topography have a beneficial or negative effect on the building?
- Are there obstructions on the site that would prohibit solar access or natural ventilation?
- Does the addition of our building have detrimental effects on adjacent structures' access to light and air?
- Do local vegetation, landform, and buildings affect prevailing winds, and in what way?

Macroclimate analysis is common in BEM tools to quantify the variables of temperature, humidity, and wind related to your general location. Several BEM tools offer bioclimatic analysis to understand the relevant architectural design strategies possible within a specific microclimate. While BEM is helpful for many items, not all analytical approaches are computable or quantifiable. Two sources to further your knowledge on analyzing climate are *Sun, Wind & Light: Architectural Design Strategies*[28] and *Climatic Building Design: Energy-Efficient Building Principles and Practices.*[29] These books present several ways of looking at a site and understanding the interplay between the sun, wind, and light. Further, these books infuse a bioclimatic methodology into the design of the building in much the same way this book continues to use BEM to validate the design decisions architects make beyond understanding the location and site.

This chapter reviewed the nature of weather files used in BEM tools, explained how to visualize climate information, and suggested what questions to ask of the macro- or microclimate. Understanding climate is a step in the right direction, and the next several chapters broaden this groundwork for how climate influences building design.

Exercise: Define the Climate Opportunities

What happens behind the curtain of a BEM tool? To understand this, gather climate data used in the BEM. The software is likely using a weather dataset defined

Table 3.13 Average hourly statistics for dry bulb temperatures (°C).

Time	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*Jun.*	*Jul.*	*Aug.*	*Sep.*	*Oct.*	*Nov.*	*Dec.*
0:01–1:00	−12.9	−10	1.4	4.9	9.6	13.5	16.7	17.7	16.2	8.2	3.3	−4.1
1:01–2:00	−13.2	−10.4	1.1	4.6	9.4	13.4	16.4	17.4	15.7	8	3.2	−4.3
2:01–3:00	−13.5	−10.9	0.7	4.2	8.8	13.3	16.2	17.3	15.6	7.7	3	−4.5
3:01–4:00	−13.7	−11.1	0.5	3.7	8.5	13.3	15.9	17.1	15.4	7.7	2.8	−4.9
4:01–5:00	−14	−11.5	0.2	3.8	8.4	13.3	15.9	16.9	15.2	7.6	2.6	−4.8
5:01–6:00	−14.3	−11.7	−0.2	3.9	9.4	14	16.6	17.3	15.1	7.4	2.3	−5.2
6:01–7:00	−14.7	−11.9	0.4	4.8	10.5	14.9	17.6	18.3	16.1	7.8	2.4	−5.3
7:01–8:00	−14.7	−11.7	1.8	5.8	11.7	15.9	19	19.7	17.5	8.9	3	−5.2
8:01–9:00	−13.8	−10.3	2.9	7	12.8	17.2	20	21	19.1	9.7	3.8	−4.4
9:01–10:00	−12.7	−8.5	4.1	7.9	14	18.5	21	22.1	20.5	10.6	4.7	−3.1
10:01–11:00	−11.6	−6.9	5.3	8.8	14.6	19	21.9	23	21.5	11.6	5.6	−1.9
11:01–12:00	−10.4	−5.7	6.4	9.4	15.5	19.4	22.5	23.8	22.3	12.4	6.2	−1
12:01–13:00	−9.6	−5	7.2	10.2	16.1	19.4	23	24.3	23.1	12.6	6.7	−0.2
13:01–14:00	−9	−4.4	7.8	10.3	16.4	19.7	23.3	24.6	23.2	12.8	6.8	0.2
14:01–15:00	−8.8	−4.3	7.9	10.4	16.5	19.6	23.4	24.2	22.9	12.7	6.9	−0.1
15:01–16:00	−9.2	−4.7	7.4	10	16.1	19.8	23.1	23.7	22.6	12.1	6.3	−1
16:01–17:00	−10	−5.6	6.7	9.1	15.3	19.2	22.5	23.1	21.6	11.2	5.6	−1.4
17:01–18:00	−10.6	−6.5	5.6	8.5	14.3	18.5	21.5	21.9	20.1	10.2	4.9	−2
18:01–19:00	−11	−7.2	4.5	7.4	13.3	17.4	20.5	20.8	18.8	9.7	4.6	−2.7
19:01–20:00	−11.5	−7.8	3.6	6.8	12.1	16.1	19.2	19.8	17.7	9.3	4.2	−3.1
20:01–21:00	−11.9	−8.3	3.1	6.2	11.5	15.4	18.4	19.1	17.2	9	4	−3.4
21:01–22:00	−12.3	−8.8	2.3	5.9	11	14.8	17.9	18.6	16.7	8.9	3.9	−3.8
22:01–23:00	−12.4	−9.1	1.9	5.6	10.6	14.3	17.3	18.3	16.6	8.5	3.3	−4.1
23:01–24:00	−12.7	−9.4	1.9	5.2	10.1	13.9	16.9	17.9	16.3	8.4	3.3	−4.3
Max hour	15	15	15	15	15	16	15	14	14	14	15	14
Min hour	8	7	6	4	5	4	4	5	6	6	6	7

by the *Climate Design Data 2009 ASHRAE Handbook*. What is this exactly? Here is how to find out.

- Find the weather files for your area
  - Specific for EnergyPlus: https://energyplus.net/weather
- Download a STAT weather file (easier to read)
  - Open with a text or notepad editor and find some weather data you are interested in.
- Pull this data into a spreadsheet program, and create conditional formatting rule(s) to highlight specific data ranges to analyze.
  - The example in Table 3.13 highlights temperatures in Augusta, Maine that fall within 20–24 °C or 68–74 °F and then those below 20 °C to 0 °C. The chart identifies a period of the year when outdoor temperatures fall within a comfortable range. This tells you that it is cold in Augusta most of the year and that heating is therefore a major requirement to maintain comfort.

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4 Energy Modeling for Architects

Defining the Energy Modeling Context

Building performance simulation (BPS) is not new in the process of building design. Like a virtual simulation, physical handmade models and drawings are key abstractions representing functions of particular building elements. BEM is an aspect of BPS representing energy performance within a building.

Simulation is an abstract process that seems to happen somehow mysteriously on our computers or in the cloud. To demystify this process, imagine a solar simulation an analog sundial creates with the sun. Before we could turn on the sun in the design software, we would build a physical model of a sundial based on our latitude and simulate where the sun would be coming from. In design, a sundial on a physical model of our building aids designers to leverage this information and improve window placement, design shading devices, or make massing changes. BEM is essentially a super-powered version of the sundial, except simulating an entire building's annual energy use, climate conditions, and operations. Energy modeling might feel like magic; however, there is a lot of history and knowledge embedded in the calculations that the simulation runs in BEM.

If you are looking to begin BEM within your company, it is important to understand your current software landscape and how BEM will help. The most common use of BEM is to achieve performance compliance with rating systems, codes, or other jurisdictional standards. The process of using BEM for compliance with California's Title 24, IECC, and ASHRAE 90.1 can be understood linearly, and Figure 4.1 describes how the majority of buildings utilize BEM.

As an alternative to the standard compliance practice of BEM, architects in charge of the energy modeling process can potentially unlock more energy savings using BEM early and often throughout the building design. Sharing this thought is the AIA, which said in its 2013 progress report for the AIA 2030 Commitment that "as design teams incorporate these [BEM] tools into their process, value is added to the owner through energy savings signifying a change in architectural practice."[1]

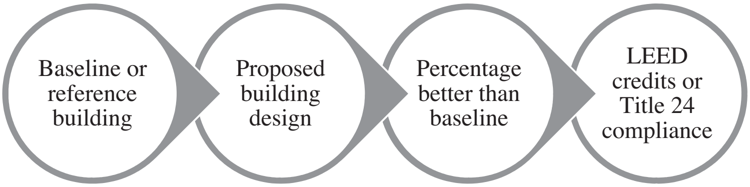


Figure 4.1 **Typical building energy modeling process for performance-based compliance for LEED credits and California Title 24 based on ASHRAE 90.1.**

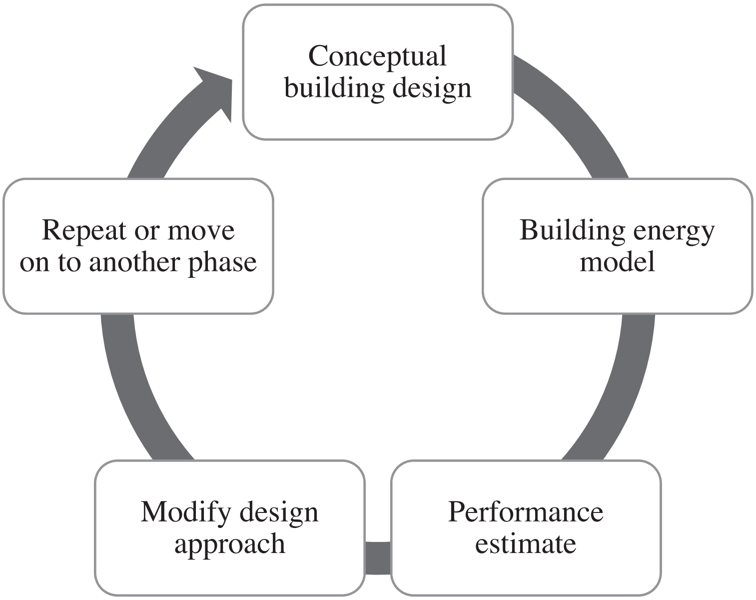


Figure 4.2 **Using BEM early and often starting at the early stage or conceptual design as a cyclical iterative activity.**

Instead of a linear process for compliance, testing design parameters can be understood as a cyclical process (Figure 4.2).

BEM Tools

The choice of which BEM tool to use will also influence the amount of data required and the level of detail needed. Not all BEM programs are well suited for early design, nor are they all adequate for whole-building energy analysis or approved to provide the necessary certifications. Choosing the right BEM for what you want is important, and two key factors to consider are at which point in the design process and for what purpose the BEM tool is used.

The AIA and others have reviewed BEM tools for functionality, features, usability, and interoperability. Functionality is important to assess what the tool can do; not all programs, for instance, can create pretty pictures of the analysis, nor do all provide hourly detailed data of an entire project simulation. Others may lack some features such as daylight and natural ventilation in their simulations. Next, architects prefer programs that are easy to use, i.e., have high usability. The creator

of the now discontinued Ecotect program, Andrew Marsh (an architect himself), incorporated some basic wizards or self-guided palettes into Ecotect that led you through the inputs required for the type of analysis you wished to complete. This helped to make Ecotect an early player for architects who wished to leverage BEM for design.

Each BEM tool's features are its distinctive attributes, and they include different analysis processes or default templates—essentially, specific elements that aid in our input and output from the software. How they operate with other software and their interoperability with your BIM or CAD program is a pathway to understanding BEM's applicability and ease of adoption into your work. Features can enhance issues with the software's usability, making it either easier or harder, and affect how well it might fit within business operations.

Unfortunately, the limits of these programs' functionality and features eliminate many BEM programs for practical use by architects. Shady Attia et al. reviewed 392 energy modeling programs and determined that nearly all were created for more engineering-based decisions, leaving only 40 that were built for the architectural decisions made early in the design process, including several that promote their so-called "early design" functionality.[2] What we can conclude from this is that there is no one-size-fits-all program for BEM. Each individual and firm should assess a program's usability for its particular needs and perhaps even consider specific staffing or consultants to supply the expertise needed. Architects or engineers entering this field will find a variety of BEM tools from which to choose, those that stand alone, act as an external interface to a simulation engine, or serve as plug-ins to BPS programs.

Consider these types of BEM tools; all are powerful and complex. In addition, they possess different features and function in a variety of applications. For more information on the specific software available, there are a couple of publications and reviews to reference. First, the most extensive list is IBPSA's Building Energy Software Tools Directory;[3] then the AIA's *An Architect's Guide to Integrating Energy Modeling in the Design Process*, which reviews a few;[4] followed by Østergård et al.'s review paper on *Building Simulation Support*;[5] other BEM evaluations by Thomas Reevese et al., in *Guidelines for Using Building Information Modeling for Energy Analysis of Buildings*;[6] and finally Drury Crawley et al.'s 2008 paper, "Contrasting the Capabilities of Building Energy Performance Simulation Programs."[7] Not to forget Jan Hensen and Attia's work mentioned earlier. Through these sources and in this book's Appendix, the reader can find a comparison of some key considerations for 24 BEM tools.

BEM Design Process

Climate and building geometry are two key elements of early architectural considerations for evaluation.[8] This leads to an important question: When does BEM

occur during the design process? As discussed by the AIA,[9] there are four key phases in the architectural design process where energy modeling is well positioned to aid in energy-based decisions: Pre-design (PD), schematic design (SD), design development (DD), and construction documentation (CD). Within these typical phases of an architectural project, MacLeamy from HOK[10] proposed a similar diagram (Figure 4.3) showing the optimal project delivery curve.

The design process published by the AIA in 2012 outlines a number of uses for BEM during each of these phases, as shown in Table 4.4. Similarly, Grinberg and Rendek outlined 12 information categories for energy modeling throughout the building design process.[11] However, they do not identify when in the design process these items should be evaluated, discussing instead how project teams should prioritize these strategies and use the team's expertise to determine when and where to conduct energy evaluations. Neither publication commits to specific recommendations as to what one would model during design.

The AIA's outline of activities and phases is a good start in terms of integrating BEM into the building design process. These items align with the design process defined by the AIA in its *Handbook for Professional Practice*. For instance, in SD, the scale, scope, and size of a project are generally defined. Drawings commonly used to demonstrate these aspects are site plans, floor plans, elevations, and key sections, as well as ideas about materials, systems, and assemblies.[12] BEM can evaluate siting, orientation, envelope construction, passive strategies, and others in the PD phase, enabling the architect to reach a level of confidence in selecting key alternatives during SD.

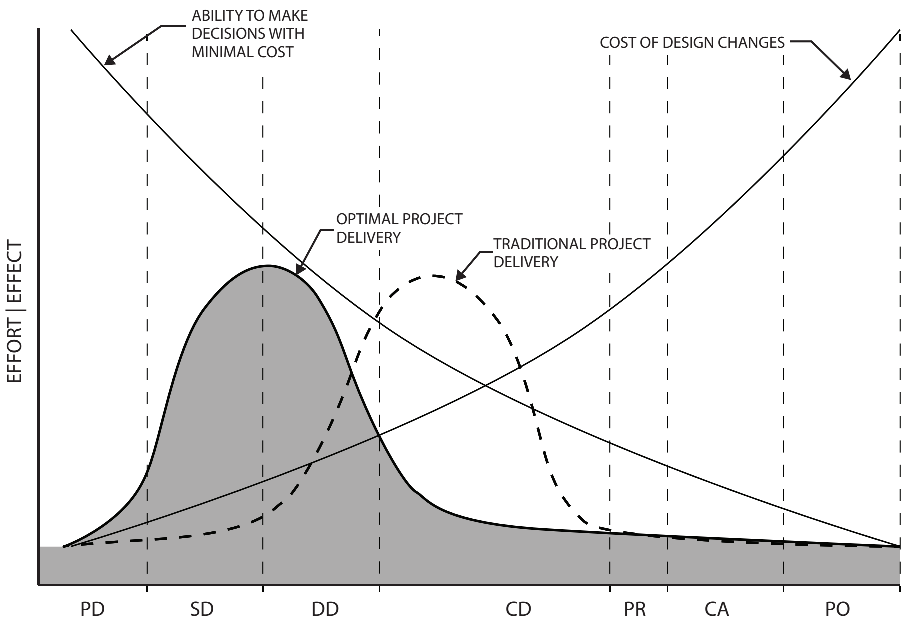


Figure 4.3 **Author's recreation of MacLeamy's optimal project delivery curve.**

Table 4.4 **Comparison of BEM use in building design based on phase of development, adapted from *An Architect's Guide to Integrating Energy Modeling in the Design Process.***

Design phase	*AIA recommendations*
Concept (pre-design)	Siting Orientation Envelope construction Daylighting Passive strategies Reduce loads
Schematic design	Rough baseline Test energy-efficiency measures Set up thermal zones HVAC options
Design development	System alternatives Refine models Baseline vs. alternatives Specific products Control strategies Quality control
Construction documents	Final design model Quality control check Final results Submit for code compliance

Level of Detail

As a building evolves, so does the information we have about it and its level of detail or development (LOD). **LOD** is a term common in the use of BIM to describe the amount of information modeled during specific points of the design process.[13] As we begin our design, we have very little information and therefore a low level of detail—zero, in fact, which equals a LOD of 000.

Following along with the LOD development is similar to following along with a BEM, including the different levels of accuracy in the model. Since there are few details known at the onset of a project, the number of assumptions input into the BEM is quite high. However, as the LOD or our knowledge about the building design increases, the assumptions drop and the accuracy of the BEM increases. An early BEM model is not accurate in terms of actual energy usage or cost information; once a building is commissioned and utility information collected, only then can the full level of development be verified.

In association with the LOD, the AIA suggests that the BEM may evolve simultaneously with the BIM.[14] Early on with a LOD of 100, energy and environmental issues can be identified and performance strategies determined based on basic volume and area. From here, conceptual designs produced during the LOD 200 phase may start to spell out our assumed system types and produce initial outputs from the BEM. At an LOD of 300, approximate simulations may

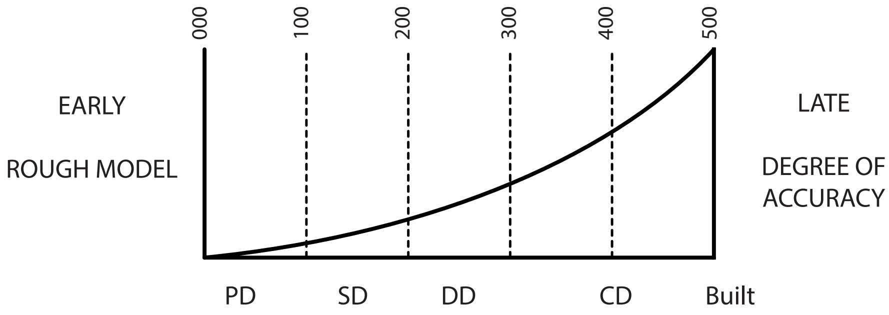


Figure 4.5 **The evolution of the BEM showing LOD and the increasing accuracy of the energy simulation.**

accompany other model outputs. For the LOD of 400, precise simulations are possible, based on the specific manufacturer and systems designs. Then, at the conclusion of the design process, the verification of the simulations against the actual operations of the building occurs at the LOD 500 as-built model.

Most of the industry follows this path to define what to expect of the BIM during the building's development. LOD is helpful in providing milestones and deliverables for a project, and in the case of BEM, this is valuable to understand since a project typically does not start from nowhere and does not go on forever. Outlining the LOD in a diagram or workflow (Figure 4.5) can show the project's beginning and end tied to specific key decisions that occur during the SD phase early in the building project. Part of this involves critical involvement by all team members so they can base their initial assumptions on the best starting point understood by all involved.

Simple-box BEM

A mentor and colleague of mine once said that before you draw a line on a blank sheet of paper you must first get a feel for the page—the space you are about to mark on. Similarly, before you begin your BEM, you must play around in the sandbox to get a feel for how the material works, moves, and is shaped. Modelers get a feel for the model they are making by creating a study model—sometimes called a white-box model—to conduct preliminary analysis of the building. SketchUp is most famous for its white-box look to modeling, but essentially you start the process by modeling a simple-box, about the size and shape of your building to play with. Early sandbox, simple-box, or white-box models often use default data for HVAC systems and basic defaults for window–wall ratio, building geometry, and size.

At this point in the design process, nothing is determined. Having a simple-box model to play with is key to understanding the various inputs needed before generating results. Initial runs may produce errors because of missing inputs or results outside the acceptable range. The BEM now recognizes the building

geometry and correctly defines walls, roofs, floors, and windows. Running early simulations helps make sure you have the inputs right and defined well enough for error-free simulations later on. With this information accurate, the simulation runs smoothly and the BEM tool produces outputs.

Another option related to early simple-box modeling may be a shoebox model. While the simple-box model represents the whole building (or perhaps just a major chunk), the shoebox model is a typical representation of a small part of the building—perhaps just a typical room or floor plate. The shoebox simplifies the BEM to the most basic and important parts you wish to understand through your analysis. Shoebox models may live beyond the early phases of design and be ideal for later analysis, as a shoebox can represent repeatable building elements so the BEM does not need to simulate the entire building. In this instance, you can multiply the individual shoebox simulation results by the number of instances in the entire building to produce whole-building results. For very large or complex buildings, or for complicated analysis, using a shoebox model might be the only option, shown in Figure 4.6. However, as discussed and depicted in the simulations presented in Chapter 7, one can see that this method might over-simplify the building.

Now that you have a feel for the model, you can play around in the sandbox to become familiar with the user interface, creating geometry and modifying the various inputs to change the simulation results. At this stage it is also helpful to produce results, learn to download the data into word-processing software or comma-separated values (CSVs), and create graphs and mockups of the analysis style and format you expect to produce at the end. Here you can complete a dry run of how the BEM will aid the design team in making their decisions.

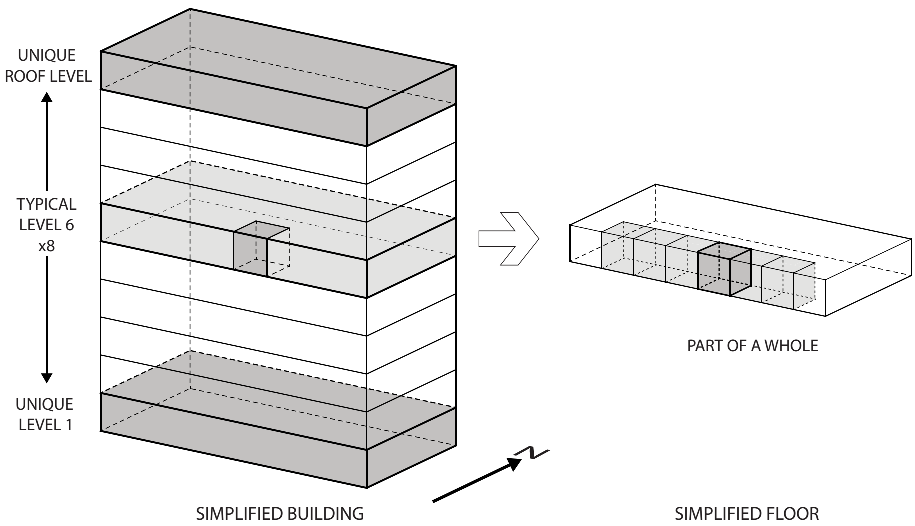


Figure 4.6
Diagram showing examples of various methods to define the shoebox for BEM.

Early Evaluations

There is no systematic protocol for using BEM during the early phases of design. Though several authors have proposed frameworks and some practicing engineering and architectural firms have incorporated BEM into early design, there are many common decisions made during the PD and SD phases that can benefit from BEM evaluation and analysis.

Along with these early design decisions, the use of BEM during the design process that we propose follows the optimal project delivery curve by MacLeamy, as shown in Figure 4.3. Connecting common design decisions made early shows that the use of energy modeling has the potential to occur often and affect related design decisions regarding energy. Support for this claim comes from the AIA in its 2013 report on progress toward the 2030 Commitment. The report measures the architectural profession's goal of reducing carbon emissions to zero by the year 2030, and shows an increase of 20 percent energy savings for those projects that use BEM, though the 2014 report goes on to state that 47 percent of the gross square footage built is designed without the benefits of BEM.[15] Clearly a critical territory, this section speaks to our thoughts on addressing this deficiency, and the benefits of using BEM early in building design.

Using MacLeamy's curve and the items in Table 4.4, Figure 4.7 highlights a framework for BEM. Within the process of design there are many factors that can be evaluated using BEM before completing SD. Assessing the site, orientation, envelope, daylight, and building geometry along with other passive strategies should inform the building's SD. To make the best decisions, BEM is often the only method for understanding a design's effect on energy.

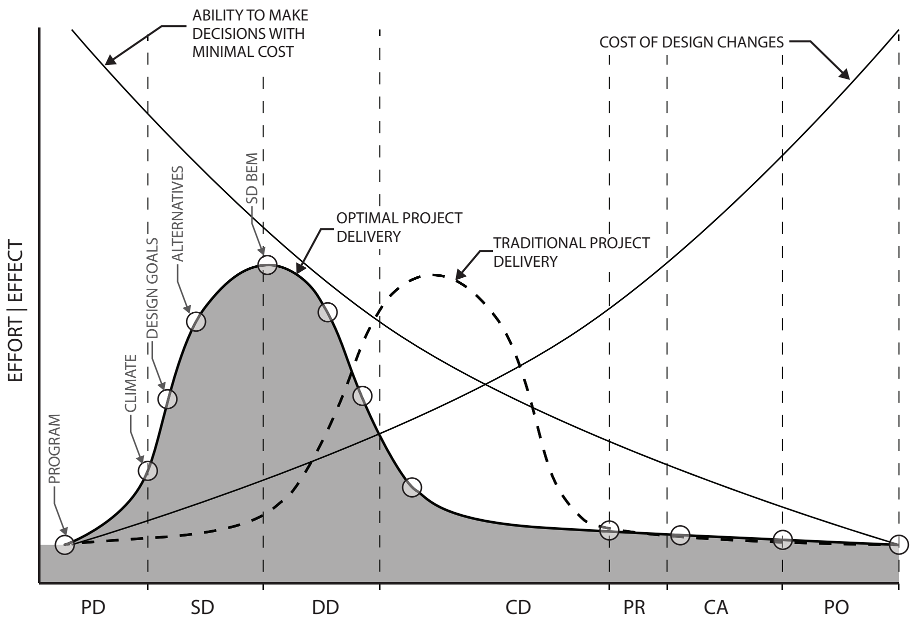


Figure 4.7
MacLeamy's curve of the optimal design process incorporating the BEM design framework.

Schematic BEM Framework

During the SD process, BEM serves as a measurement tool for informing performance-based decision making and maximizing architecture's role in energy conservation. Based on the concept that in an idealized design process (shown above), most of the major design decisions are complete at the end of SD, the BEM should then also represent a complete building solution that measures how a project consumes energy. To reach this point of clarity, early iterative use of BEM throughout SD allows designers to analyze the building use and program, assess the climate and site, prioritize design goals, and evaluate alternatives to reaching the SD BEM. During PD and into SD, early design issues are introduced and evaluated using BEM in accordance with this framework. Beginning the process is introduced next in Chapter 5, with specific evidence and examples of how this is accomplished.

Program analysis, or architectural programming, involves defining the building scope and the type of building that the client, owner, or developer is looking for.[16] Crucial for integrated project delivery, this early research and program analysis identifies specific project needs, goals, and objectives. Identification of the spatial qualities and character occurs during this stage, and using BEM aids in validating and forecasting energy usage and associated costs. At this point, the BEM may have very little information; however, by basing these decisions on a known proxy or precedent example (as is common during this phase), architects and owners can forecast a building's energy use or assess different programmatic mixes. Alongside program evaluation, early space planning analysis can establish energy-use profiles and environmental needs for different spaces. The program analysis involves defining relationships, dimensions, uses, and quality characteristics for the various spaces incorporated into the building. Many of these defining characteristics can benefit from the BEM analysis.

Next, assessing climate furthers a designer's ability to understand a building's behavior related to energy use. Whether the building is located in a hot or cold climate, using BEM is an excellent way to visualize local weather patterns by showing us where the sun is and when, how the wind changes over the course of the year, how much the temperature fluctuates, how high the humidity levels are, and what kind of sky conditions exist for each hour of the year. This is such an imperative topic that a complete chapter of this book is dedicated to covering climate.

Following or concurrent with climate is site analysis. Siting decisions evaluate the building's orientation related to zoning issues and setbacks, environmental and natural features, and local microclimate and weather patterns. Here, BEM can aid in parsing and visualizing local weather data for analysis. Arming your design team with robust information about your project's program, climate, and site allows you to begin the design process with a wealth of information that can be synthesized into a complete building.

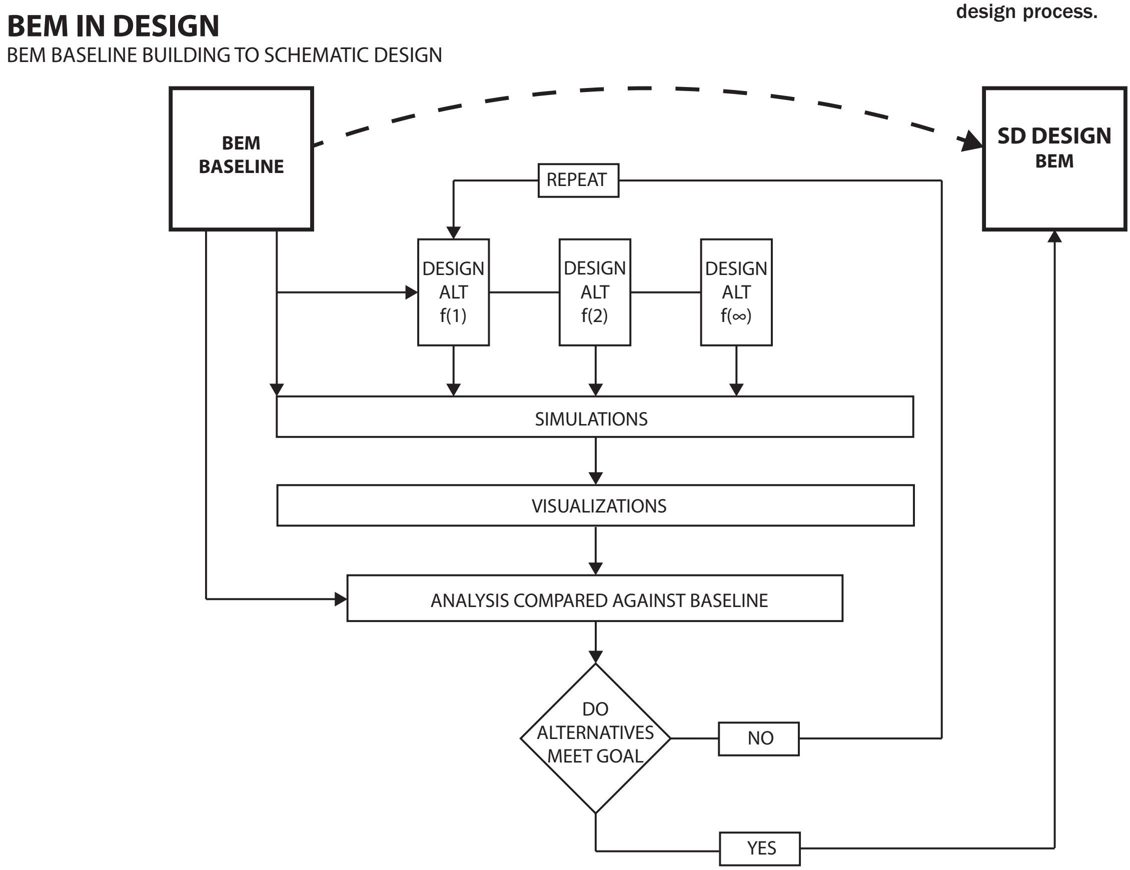
Leveraging this background information, BEM can help prioritize the project's design goals by identifying which design alternatives, passive solar strategies, materials, and envelope technology are best suited for a particular site, climate,

and program. Prioritizing these items requires ongoing modeling and analysis to visualize how various design goals stack up to impact energy savings.

Once the sustainability and energy performance goals for a project have been defined, investigating design alternatives and strategies helps maximize architecture's ability to conserve energy. Since this occurs early, using BEM to evaluate the building's architecture may or may not include specific HVAC systems performance. Identifying clear design alternatives helps measure with BEM which specific passive solar strategies and materials will achieve the most energy savings, and often this will be not just one, but a combination of several alternatives.

Proper programming using BEM can identify the right mixture of uses to help balance energy loads. Additionally, BEM can help assess whether the building design responds appropriately to the climate, or whether its orientation and reciprocal site relationship embraces the sun and the local context. It can also assist in identifying which design alternatives, materials, and passive solar strategies are ideal for maximizing energy conservation and operational utility costs. Addressing these issues and more, the SD BEM represents an early synthesis of a building's complexity into a comprehensive whole (Figure 4.8).

Figure 4.8
Diagram showing the logic and steps involved in a BEM design process.



This early BEM framework—beginning with program analysis, followed by climate and site analysis, identification of goals, and the evaluation of alternatives—aids design teams in reaching the SD BEM. Getting to this point provides architects, engineers, and the rest of the team with measurable information about a building's energy performance early in the design process. The conclusion of SD typically involves articulating the total size, scale, and scope of a project in various drawings. Along with these representations, the team can present information about how effectively the building will perform and meet energy consumption targets.

After an early SD BEM milestone, the building design will continue to develop in complexity and clarity. The next phase, DD using BEM, will again cycle through a range of iterations to explore energy consumption information to aid in design decision making.

Design Development

Using the specific strategies and concepts from SD, the DD phase further expands and resolves various aspects of the building. Design is more specific and increases from a general overview of the total building to more specific attributes of space, materials, and the building's overall shape and appearance. At the completion of the DD phase, the drawings produced are similar to those at the beginning, but they include more details expressing the entire picture of the building and all the things that make it complete.

As outlined by the AIA, during the DD phase the BEM explores systems alternatives, incorporates specific materials and products, investigates different control strategies, and undergoes a level of quality control to establish a baseline and design model comparison. However, as any architect knows, the building's design is nowhere near complete. The iterative cyclical process continues to evaluate how to incorporate specific materials and products, different systems, controls that affect the building's functionality, the articulation of the fenestration, and spatial organization. As such, BEM continues to be an important ally for measuring the energy impact of these developments.

The DD BEM has a higher degree of accuracy in forecasting energy use and costs. Given the increased amount of detail developed during this phase, the BEM has grown in complexity and accuracy related to how it represents the building design in the simulation. Since the model contains more information, there are three issues to consider. First, simulations may take longer to complete; second, changes to the BEM will take more time and effort; and third, detailed inputs and designs for mechanical, lighting, and controls may be necessary. Not all BEM tools are suited for the complexity of these inputs, and furthermore, not all engineers and architects may be adept at understanding the necessary inputs. Considering the increased complexity of the building design and resulting BEM representation,

trusted expertise is a must to ensure quality control of the model. Whether this occurs in-house or from a consultant, knowing that the BEM meets the project expectations remains crucial.

Unexpected Results

We should note—and feel it necessary to share—that both beginners and experts encounter unexpected hiccups when using BEM, and taking these seriously is part of knowing your BEM. Results are meaningful only if they stem from intentional changes as opposed to unintentional ones. A BEM can include a bug, and this depends on the design tool—we've encountered them in every BEM tool we've used. In fact, authoring Chapter 7 produced many. Running simulation after simulation, one begins to see either a pattern emerge, or no pattern at all; when this occurs, the first question to ask is whether this is a result of the design question or an anomaly in the BEM.

Do not be discouraged; such accidents can be resolved and worked through. To troubleshoot the problem, first review and double-check all settings across the design iterations, confirming that your units, numbers, and all other settings are correct. Also, check your building geometry to ensure you do not have anything extra hiding or modeled as part of the simulation; this will eliminate human error. Next, flex your model to see if it is indeed a function of the BEM tool. If there is a cause for the anomaly, test it by changing something specific to find the root cause. If you continue altering a specific component and nothing changes in the model, that component may not be causing the problem. Another approach is to read the help menu and explanation of how the BEM simulates the results; herein may lie an answer as well. Depending on the BEM methodology and what and how it calculates, a small discrepancy could result in certain aspects of the model working unexpectedly. Another alternative is to complete the analysis using another BEM tool. If both BEMs yield comparable results, they are likely correct. Finally, depending on your service agreement, the software company itself may be able to examine the model, or you can try sending it to a friend or online user group to investigate; a third party may easily find something you've missed.

Making the BEM

To begin the BEM, you first need to construct the geometry within or for the energy modeling software, and not all programs perform consistently in completing this task. As such, you should wait a minute before leaping into the BEM! It's vital to know that the architectural methods for building a computer model using software are not the same as the ones used to virtually define an energy model. This can be frustrating (trust us, we know!); however, it can also free you from

overthinking unimportant aspects not considered in modeling energy use. The BEM tool for Revit has benefits within this territory by allowing you to export the building model geometry to Green Building Studio using a gbxml file without changing or remodeling the building.

The architectural approach to modeling a building in design software is that the building walls, floors, roofs, and other elements have a spatial dimension and thickness. A wall, for instance, might be six inches thick to represent the different layers of the assembly. Within the wall there is a window, and that window might be one inch thick. Between the wall and the window is another element, a window frame, and so on. Models created in this fashion help represent the construction, materials, and other aspects of a building that need designing; however, an energy model cares about none of these things. An energy model understands your building in a different way than the architectural model, shown in Figure 4.9.

In an architectural model, the size and dimension of walls, floors, and roofs matter. The BEM simulation requires a different representation of the building to understand the thermal properties of the basic building envelope and calculate the dynamic transfer of energy through these elements. For the purposes of an energy model, the architectural model is abstracted and simplified, as shown in Figure 4.9. Depending on the BEM program used, the building envelope may be simply a single surface with different material properties for the walls, windows, roof, and floor. Within this simple box, the room we would model architecturally is now just a thermal zone that contains spatial properties related to use, occupancy schedule, operations, and thermal comfort expectations. Once the fabric of the building and thermal zones are understood by the energy model, the simulation uses the climate to determine the heat loads, gains, and losses throughout the building fabric to maintain comfort within the thermal zone.

How do we then reach the point of creating the BEM geometry? That all depends on the energy modeling software used. Some programs have very simple, basic graphical user interfaces to create building geometry; others—plug-in BEMs—move your architectural model geometry into the BEM program or interface with the design software, allowing you to create the geometry. There is no one correct workflow, but perhaps just a workflow best suited for what you want to do. Some professional energy modelers will also use the BEM program and rebuild the geometry using the software. If you are using a BIM tool, some programs allow transfer of the building model directly into the BEM either as an extension of the BIM or as a file type into the BEM. You might also use the design software to model the geometry for the BEM, which is likely the best option for the architectural audience.

Now that you have created the building geometry for BEM, you can just click Go, right? Hold on, there! There are still necessary inputs before beginning your energy simulation. Discussed next are common inputs for residential and commercial baseline BEM examples. One will see that there is still information necessary for completing a simulation using BEM.

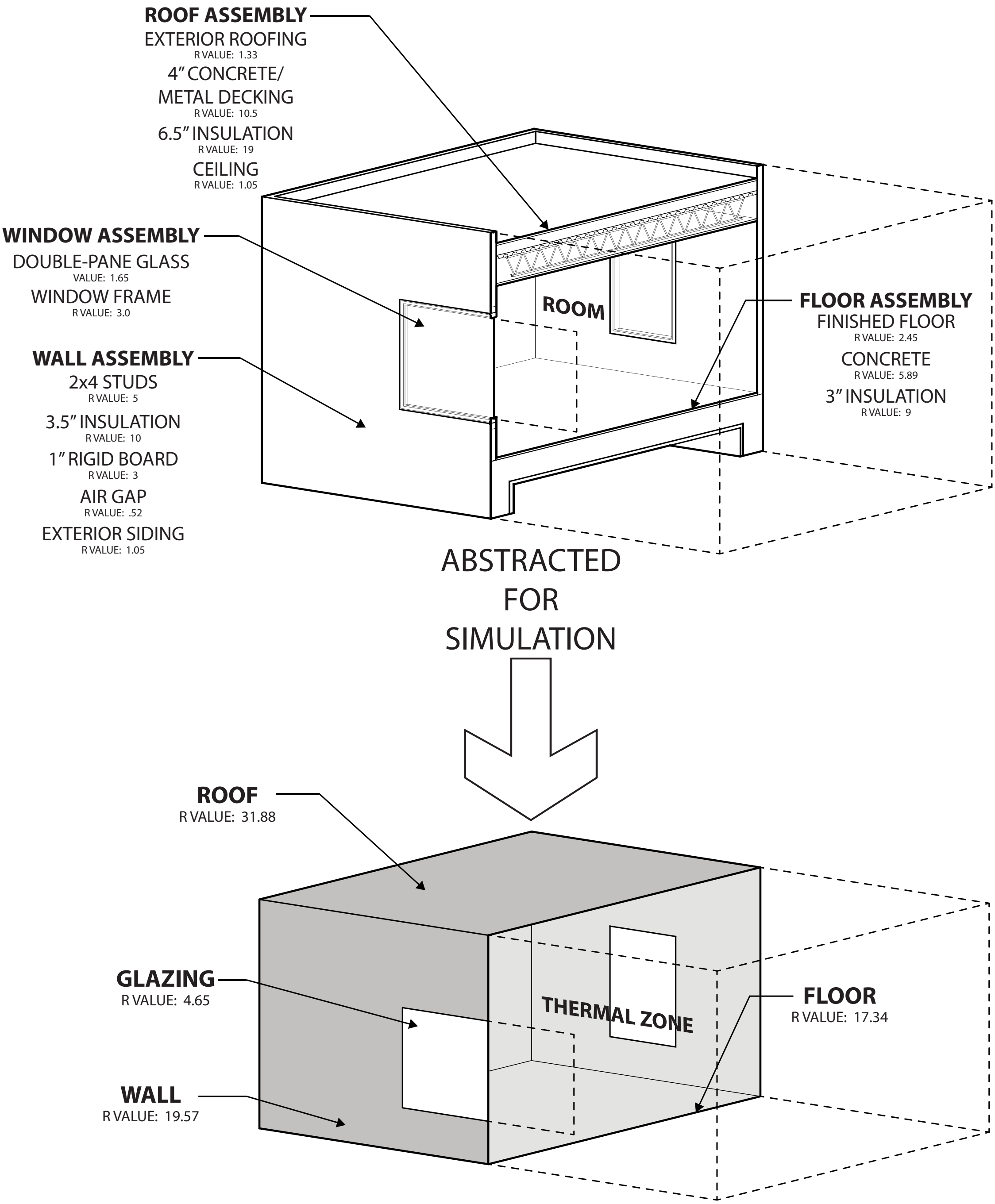


Figure 4.9 **How an energy model reads the geometry in an architectural model.**

What do you do if you don't have everything you need to complete the BEM? To begin a BEM, you need to first know your project location for the climate and the building type; these two inputs are the most fundamental elements for beginning the BEM. Without the information beyond these two basic pieces, there will be many assumptions made, creating a guessing game for many aspects of the building project during the design process. However, important decisions are made early in design that affect how a building will consume energy, and being able to evaluate them using BEM can help you make informed decisions. Assumptions can be modified as the building design develops and decisions are reached, and it follows then that the accuracy of the simulation will increase during design as more and more decisions are finalized, as shown in Figure 4.10.

In the absence of detailed information about the design, a designer can use known information about the building type to drive some of the BEM inputs. An office, for example, has a certain population density based on the building square footage. Therefore, we can define the number of occupants and the working schedule based on an 8 a.m. to 5 p.m. workday. Next, we can assume that our building will meet current code and can set the R-values for the building materials and the U-factors for the fenestration accordingly. Code also dictates a certain percentage of windows for lighting and ventilation based on the total floor area, while IECC spells out minimum efficiency ratings for HVAC systems. Basic details such as these are ways to begin the BEM, establishing our starting point for conserving energy.

Beginning a BEM

A BEM model requires several key inputs to begin. As identified previously, climate and the weather file are important items to evaluate and understand when starting

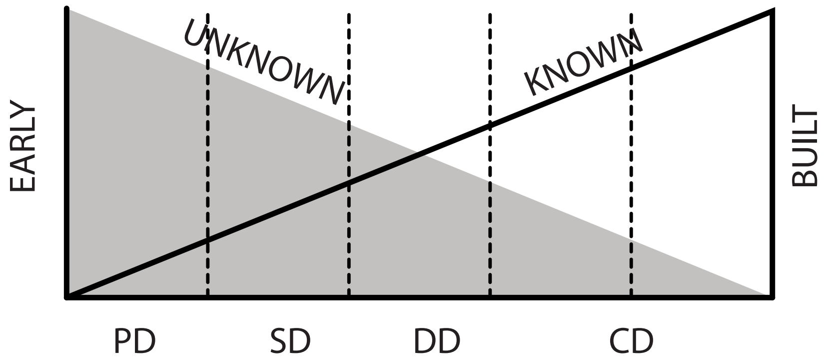


Figure 4.10
Conceptual graph of the information and its accuracy used in a BEM.

your BEM, since the BEM needs to know your project location to access the necessary weather data, and without this data there would be no BEM. The model parses the weather data, the typical meteorological year, to determine how a building performs at the location identified. Alongside the weather, other location data may include site geometry. Other elements to create could include defining other aspects of the site such as context and vegetation; however, these are not necessary to begin. Along with location, the energy and cost data associated with your project utility provider is however, necessary, and the fuel mixes and local utility costs will help ground the project in realistic data for utility cost estimates and emissions. Next, operations data related to assumptions on how your building is used, its type, schedule, lighting, occupants, and equipment needs should be considered. Before or after these inputs comes the definition of building geometry, fenestration, and materials in either the BEM or another design program (where it is then imported into the BEM software). The mechanical and electrical systems often follow the loading of these items into the BEM.

There are those input elements of the BEM listed above that are either static or dynamic. Static components of a BEM are those that, once built, will not change, such as the walls, roof, and window elements within the model. The dynamic components of the constructed building change over time, and include the people, lights, air, water, fans, etc. that vary. The BEM's purpose is to combine both the static and dynamic components within the simulation to predict the building's energy use.

Location

At this point, you will have site constraints and zoning issues to either consider or ignore. For the purpose of this discussion, we will ignore specifics already discussed such as setbacks, site geometry, and topography, and instead focus on the issues that will directly affect the BEM outputs. If your site is urban, modeling the existing building context and forms is essential for the shading of your building and any shared party walls. If the site is suburban or rural, exterior elements will have less of a direct effect, and using a generic site is possible depending on the goals of your initial BEM. Depending on the building location, the model can then develop from this point or take other site constraints into consideration. Some BEM tools come with different settings for urban, rural, and suburban contexts, and modifying this contextual information changes how a BEM understands and calculates results.

Other location-specific components that feed into the BEM are the fuel mix and utility costs. Your local power plant may or may not be where you get your power, and many states have defined fuel mixes for their portfolio of electricity generation. While we may not know whether our electricity comes from natural gas, petroleum, coal-fired, or renewable sources, this mix of fuel is something

BEMs use to calculate the emissions (such as CO_2) produced from a building's energy consumption.

The utility cost information comes from your local electricity or gas provider. The cost per therm of natural gas or per watt of electricity allows a BEM to calculate annual utility costs. Typically, such costs are important in evaluating the decisions or choices for systems or other changes to the design using a BEM. Beyond the more straightforward costs, the BEM may factor in time fluctuations and costs based on peak hours or off-peak energy consumption, also showing the anticipated cost escalation over time for longer lifecycle calculations.

Operations

Information to know when starting the BEM includes the program and building type. Your building type has a specific space use(s), such as retail, office, residential, warehouse, or a mix of these. The type of use helps define occupant load—in other words, how many people are in your building and when. Understanding how many people will occupy the building (known as the occupant load) is a necessary detail to define, since how many people work or live in the building influences internal gains that affect cooling loads. Within a BEM, occupancy can either be applied to the whole building—say, for businesses, one person per 100 ft^2—or space by space. This largely depends on the BEM tool used and the resolution of the model desired. With people comes defining other operational aspects such as the occupants' schedules, the building's lighting needs, and other types of equipment to define dynamic operational energy use, often expressed in watts over area, W/m^2 or W/ft^2.

People come and go, and scheduling their occupation—called the occupancy schedule—of the building helps define when the internal loads will need to fluctuate to accommodate them, along with when lights and equipment will be on or off. If there is nobody in the building, then the lights (in theory) should not be on, though as we all know, this does not always happen. The occupancy schedule is typically set with two key numbers: the total number of building occupants, and the building's daily schedule as percentage occupied. Setting the schedule defines the percentage from 0 to 100 percent, though rarely is any building 100 percent occupied. Often, work environments fluctuate from 70 to 80 percent occupied, since people are traveling for meetings, off site, sick, or on vacation. Setting schedules for the people who occupy the building is just one aspect, and many BEM tools also have schedules for the building lights, equipment, fans, plumbing fixtures, and systems controls.

Lighting is a necessary part of a building. Electric lights in particular supplement where daylighting is not possible, such as in internal rooms or during nighttime occupation. Lighting needs change widely, depending on the building type, its space needs, and its occupancy requirements. Typically, a BEM defines this as the lighting power density (LPD) in watts per square meter

(W/m^2) or square foot (W/ft^2). Like occupancy load, and based on the BEM tool used, this value can be used for the whole building or calculated space by space. ASHRAE Standard 90.1 spells out how to calculate the LPD for these two different applications.

Buildings also use different types of equipment. Offices have copiers, phones, coffeemakers, and countless other items, all of which consume energy when they are plugged in and being used. Two aspects of a BEM relate to these uses: one is the plug load, the other is the miscellaneous equipment load. Plug loads are the transient loads users may plug in at their workspaces, such as cell phone chargers, fans, or laptops; miscellaneous equipment loads are those turned on every day, such as printers, copiers, and computers. Some tools may lump these together, while others may break them apart, define them space by space, and assign schedules for their use. Depending on the resolution and BEM tool, one could input only the plug loads and not the equipment loads.

Systems schedules are a bit more complicated, and are often tied to thermostats and controls within the spaces people occupy. Systems schedules are usually defined space by space within specific thermal zones. The thermal zone could be a room or an entire floor plate, depending on the HVAC system design. For early energy models, creating a single zone or different perimeter and core zones are typically most common approaches. As the BEM resolution increases, other tools will tie systems and their schedules directly to the specific thermal zone and the thermostats and controls within. Knowing this level of detail early on is difficult, since the specific floor plan and space layout are still fluctuating.

Geometry

Knowing total square footage and floor-to-floor height is necessary to establish the overall building volume to model for BEM, allowing you to define a generic form of your building. Following the initial building geometry and site information, we reach a key decision point in the development of the BEM: What do we want to learn from our analysis? Climate and building type drive the energy-saving strategies to maximize architecture's role in energy conservation. The interplay between these elements determines the focus of our design analysis and which building elements should be explored further, such as the geometric shape of our building.

Building the geometry for a BEM depends on the analysis tool used. Revit, for example, has two methods for building geometry: conceptual massing and building components. The two are ideal to explain the common energy model definition of geometry versus the typical architectural model. The conceptual massing is purely for building form—the volumetric container. The volumetric container may be a box, a random shape, another letter shape, or a composition of

many shapes. These are conceptual because they are merely basic surface models where the outward surface of the geometry modeled represents the exterior walls, roof, and ground floor. Modeling other aspects of the geometry are planar surfaces or divisions of the surface into other elements for windows, interior floors, and shading devices. The conceptual model then is a simple surface representation of the building, often referred to as the building envelope or fabric.

Most BEM tools and simulation engines only recognize this simplified version of your building's geometry. However, some BEM tools may allow more definition of the architectural model using components such as walls, roofs, and windows modeled as building elements. In the case of Revit, the program creates a relationship between the building components and the space/room tags and translates this into a gbxml file for Green Building Studio. This process simplifies the building components into the building fabric and the BEM tool.

After defining the basic building geometry, the relationship between the aspect ratio, the length and width proportions of the floor plan, and the total building height or stacking is complete. One can choose to explore issues of this geometry, different configurations of the basic geometry, and the resulting effects on energy. At this point the most compact form will likely win out, though daylighting considerations limit the building depth and could stretch the form into letter-shaped geometries. Choosing to prioritize daylighting in your design, if appropriate, will orchestrate how to proceed with the analysis of the geometry and the amount and location of windows.

Fenestration

A building's fenestration includes the windows, frames, glass, and any shading devices; including windows in the building geometry will affect the geometric BEM analysis. Without windows the analysis will be of limited use and potentially pointless; however, when evaluating the role of the sun's radiation on the building geometry, windows may or may not help. For instance, if the goal is to minimize the amount of solar radiation on the building's surface, completing the analysis without windows could tell us the minimal geometric form for our building. In this case, excluding windows could be one way to utilize BEM to determine building geometry.

We know, however, that all buildings must have windows; therefore, the question is what and how to introduce them into the BEM analysis? There are of course multiple pathways to approaching this, depending on the design. Additionally, windows are the most interrelated element of a building affecting energy use. Windows affect the BEM, and users must carefully include windows into their analyses. So, where do you begin?

BEM tools actually have a generic approach that involves defining the window–wall ratio (WWR), that is the percentage of the building façade defined as

a window. Some tools can actually do this for you without requiring any geometric definition of the window itself on the building's geometry. This has an early benefit in design by allowing the evaluation of WWR to determine the proper amount and generic orientation of glazing on a building façade prior to designing specific fenestration. Exploring the amount of glazing and its location on the building can help establish WWR targets for the north, south, east, and west façades of the building. However, in this case, BEM tools could apply a WWR without regard to the specific site, context, opening size, or location.

Requiring specificity of the window location for your analysis requires investing the time to model the precise window geometry. The default WWR percentage within a BEM tool is often represented as a ribbon window, so if this suits your design, you're in luck. If not, you might consider exploring the window location and distribution within the design model in more detail. Setting the window sill and window heights is an important input at this phase of the BEM development. Additionally, adding particular windows to the model can tie your analysis to design considerations of views and interior space types such as atriums and others. While the geometry of the BEM will be more specific, the difference in energy consumption between the generic WWR approach discussed above and one window in a whole-building analysis may be minimal. If you want to understand other specific impacts of glazing, choosing different analysis tools might help.

One tool specifically designed for evaluating different fenestration details during design is Comfen. Comfen is different from many BEMs in that it models only a small portion of the building, such as a typical office or a single room, a shoebox model. For detailed fenestration analysis, Comfen is ideal. Designers can explore a variety of different window configurations, types, and arrangements evaluating the energy, daylighting, and ventilation effects.

Materials

Moving beyond the generic or specific window definition in the BEM is the definition of building materials. Early on in design, we may not know which specific materials will be used, but BEM can simply understand the materials by their U-factor or R-value. Defining the R-value of the building envelope and its elements (roof, walls, and floors) is a necessary input into any BEM. This can be specific or generic, depending on the information you have available at the time.

After the material definition of the building envelope comes the definition of the building's HVAC system. Many BEM programs focus on the design of a building's mechanical and ventilation systems; however, within architectural design these aspects are usually handled by mechanical engineers. Without their expertise, one could use typical system templates or inputs to establish the system's efficiency for the BEM.

HVAC

HVAC systems typically have a significant impact on the total building's energy use. Involvement of the engineering team and careful attention to the HVAC systems throughout the design process is critical to a successful building project. Furthermore, in defining the building system comes another critical point in the creation of the BEM. Building spaces have certain needs and associated zones for a specific HVAC system, and a larger building may have many zones with different specifications for these systems. However, in an early application of BEM in design, specific spaces may or may not yet have been laid out. BEM tools therefore offer a choice between a single-zone analysis or using perimeter and core zones.

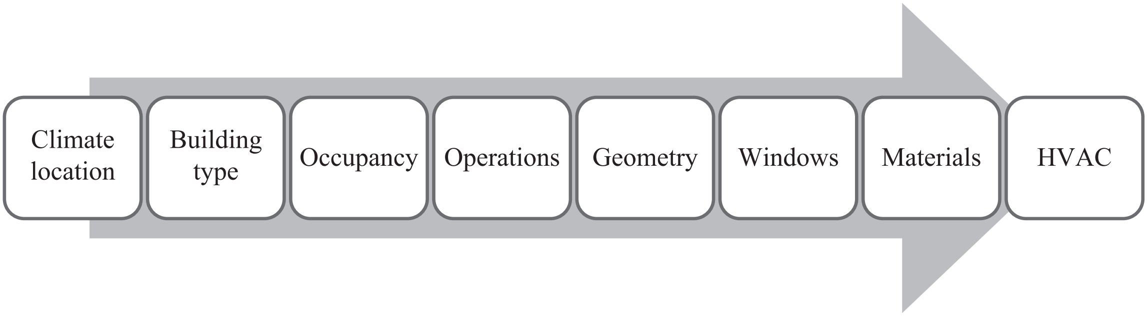
Single-zone analysis treats the whole building as one thermal zone and calculates energy needs based on maintaining the building set points uniformly across the entire zone. This is acceptable for some building types such as residences, warehouses, and small retail buildings, among others.

Perimeter and core zones are typical for larger buildings (especially offices), where the heating and cooling demands are different for the building façades around the perimeter and for the core. Heating and cooling around the exterior is typically more variable than that of the core.

Following the input of the HVAC system into the BEM, definition of the basic space uses, occupancy loads, schedules, lighting power densities, and equipment plug loads round out the initial basic building inputs. These final items could be entered first; however, in early BEM we often do not yet know enough about the design to use specifics. Therefore, basic defaults are necessary early on in the BEM, and as the design develops these inputs can be changed based on project details and priorities.

Here we could conclude with the basic beginning inputs into a BEM as summarized in Figure 4.11. From these inputs, your BEM will produce results for analysis, though some BEM tools may require more or fewer inputs, depending on their functionality. For example, Design Builder can be set for either early- or late-phase analysis and therefore requires different inputs—in some instances lumping together lighting and equipment loads into one single power density for the entire

Figure 4.11
Required inputs for a beginning BEM. The specific order of entry is less relevant than ensuring that all inputs are accurate and complete.



building. If this is an input you don't know or care about, then this is perfect for you. Other times, Design Builder—even when set for early-stage evaluations—might require more inputs than other BEM tools regarding the specific HVAC system. Whichever BEM tool you use will alter the process outlined.

Conclusion

For a BEM, not all settings may need to be modified prior to running a simulation to produce results, though by passing over these settings you are relying on the software defaults, which some BEM tools determine using code defaults or common practices. This can be beneficial early on in design since you might not know what exactly to input. While running simulations using defaults (as in a simple-box model) can provide some idea of where to focus your design efforts, moving on from the default settings is essential to diagnose and analyze what is affecting the building's energy use.

The key question answered above was how much information is needed to get started with BEM. Since the focus is on BEM in architectural design, many of these decisions occur during design, where the LOD is constantly evolving along with the building design. The BEM tool, then, needs to be able to begin evaluating our designs with very little information and allow finer-grained inputs later. To our knowledge there are no perfect BEM tools available, though there are some programs and workflows that have proven effective in using BEM from the beginning to the end of the design process. Understanding how to make design decisions using BEM requires careful attention to where you begin, and following the simple-box model there are two common BEM developments: a baseline and a goal-setting model. These points inform the topic of the next chapter.

Exercise: Identify the BEM Type and Inputs

Three key types of BEMs were discussed in this chapter. Complete definitions for each of these terms:

- shoebox model;
- simple-box model;
- SD BEM.

Reference Figure 4.11 and identify what information you have to begin your BEM, using this checklist:

- ☑ climate/location of project (have you downloaded the Typical Meteorological Year (TMY) file?);
- ☑ site context, if any, to model;

- ☑ program/use(s) for building type and amount of building occupied;
- ☑ total number of people for each program;
- ☑ program/use(s) schedule (percentage of people per hour of each day of the week);
- ☑ plug loads, lighting power density, and equipment loads;
- ☑ total building square footage and, if multi-story, the amount per floor;
- ☑ floor-to-floor height and total building height above and below grade;
- ☑ limiting site dimensions for overall main floor plan if appropriate;
- ☑ amount of exterior wall area required or desired for glazing (WWR);
- ☑ material properties (if known) for walls, roof, floors, and windows;
- ☑ mechanical and ventilation requirements.

If you have checked all of these off, you can skip the next two chapters, ha! More likely, you need to read on to see input examples for many of these items and understand how they all begin to work together in the BEM.

Notes

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3 International Building Performance Simulation Association-USA, "BEST Directory," www.buildingenergysoftwaretools.com.
4 Energy Modeling Working Group, *AIA Guide to Integrating Energy Modeling in the Design Process* (Washington, DC: AIA, 2013), 56.
5 Torben Østergård, Rasmus L. Jensen, and Steffen E. Maagaard, "Building Simulations Supporting Decision Making in Early Design: A Review," *Renewable and Sustainable Energy Reviews* 61 (2016): 187–201. doi:10.1016/j.rser.2016.03.045
6 Thomas Reeves, Svetlana Olbina, and Raja R.A. Issa, "Guidelines for Using Building Information Modeling for Energy Analysis of Buildings" *Buildings* 5, no. 4 (2015): 1361–1388.
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Conference of the International Building Performance Simulation Association ed. Etienne Wurtz (Chambéry, France: IBPSA, 2013), 121–128.

12 AIA Knowledge Resources Staff, *Defining the Architect's Basic Services* (Washington, DC: AIA, 2007), www.aia.org/aiaucmp/groups/secure/documents/pdf/aiap026834.pdf.

13 AIA, "AIA Document G202-2013, Project Building Information Modeling Protocol Form," www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab099086.pdf.

14 AIA, *Integrated Project Delivery: A Guide*, volume 1 (Washington, DC: AIA, 2007), 11.

15 Alec Appelbaum, *AIA 2030 Commitment, 2014 Progress Report* (Washington, DC: AIA), 12.

16 Edith Cherry and John Petronis, "Architectural Programming," in *Whole Building Design Guide* (Washington, DC: National Institute of Building Sciences, 2009), www.wbdg.org/design/dd_archprogramming.php.

5 BEM Baseline

In the early stages of design, you will likely have a basic program and site information for your project, with some general understanding of the amount of square footage your building requires. Before going hog-wild with energy modeling, however, there are some early questions to ask: What are the local energy code requirements for your jurisdiction? Does the client have goals beyond the codes, such as LEED or Building EQ status?

Energy codes vary from state to state, and are more often than not a recent version of the International Building Code (IBC). This international suite of codes includes the International Energy Conservation Code (IECC) and the International Green Construction Code (IGCC). The IECC code specifically uses ASHRAE 90.1 to establish an energy performance standard for buildings, with the exception of low-rise residential buildings.[1] Understanding the pertinent standard applicable or benchmarks beyond the code is a necessary early step, as it establishes the reference for a baseline.

What is a baseline? Think of it as the BEM starting point. Just as with a long road trip, you have to start somewhere, and with BEM the starting point is an understandable baseline. The baseline is set based on a commonly held reference, often used to evaluate project goals and demonstrate compliance with standards. For many of us, this reference is the energy code, presently IECC and ASHRAE 90.1 for commercial buildings. Armed with an established baseline, design teams leverage a goal-setting model to identify performance pathways for improving the energy performance of the building.

Establishing a Baseline

ASHRAE 90.1 Code-Compliant Baseline

The most common type of baseline model for your building is a BEM that meets IECC and ASHRAE 90.1 requirements. Whether demonstrating prescriptive compliance or

building an energy model for the performance pathway, this baseline simply demonstrates that your building meets code requirements. Code is, of course, a low standard of compliance, and as the baseline, it is self-referential not saving any amount of energy.

Every building we design today should meet code. Staying current with IECC also helps drive energy savings: In theory, each new version of the building code produces more energy-efficient buildings than the previous one. The ICC, U.S. DOE and various jurisdictions typically evaluate how much energy savings and cost impact they can expect from changing the current codes.

LEED or ASHRAE's Building EQ requires simulating a building design against a baseline, requiring a code-compliant, ASHRAE 90.1 building design. In this case, the baseline simulation is the final design, with the exception of some system efficiency improvements. Using this simulation, design teams can evaluate the impact of energy conservation measures using the self-referenced baseline building. Using this comparison of the percentage improvement over code determines the LEED points and a Building EQ score.

By using the baseline as a starting point, architects can compare the energy savings of different design decisions. This is important when you wish to tell a client that a particular building is, for instance, 30 percent more energy efficient than code. Knowing the baseline allows you to support your claim with sound evidence based on BEM. To begin with, use a known proxy baseline for energy modeling (see Tables 5.1 and 5.2); if you lack any specific point from which to start, be sure to track and define which standard or example the assumptions were based on. You might also want to take an average of other building types similar to yours.

Prototypical Proxy Baseline Using CBECS

Based on the 2003 Commercial Building Energy Consumption Survey (CBECS), the U.S. DOE used energy modeling to establish 16 common buildings[2] representing approximately 70 percent of the U.S. commercial stock across seven different climate zones. Pacific Northwest National Labs updated the data of the commercial prototypes and expanded the building range to 80 percent of the U.S. building stock.[3] The initial DOE buildings use the 2004 version of ASHRAE 90.1, and recent updates cover the 2007, 2010, and 2013 versions of 90.1. The data one can download spells out the E+ inputs and outputs and includes energy-use intensity end uses across the range of the 16 types modeled. It is a helpful tool for serious energy modeling beginners to validate their energy models against known proxy baseline buildings.

Additionally, the data from these different building types helps establish an understandable proxy baseline for your project type, whether or not you already have a design for your building. Using the most recent updates can assist an early conceptual energy model of a project—that is, if it fits within one of the types modeled in E+. Similar to the code-compliant baseline, these types represent typical typological buildings based on ASHRAE 90.1 to gauge energy performance.

Table 5.1 **Simulation settings used for energy-modeling residential baseline based on the Building America reference.**

	Residential baseline settings
External shading	Eave offset 2 ft. on each side
Heating set point	71 °F/21.67 °C
Cooling set point	74 °F /24.44 °C
People	0.0431/m^2
Equipment load	2.69 W/m^2
Heating efficiency	0.8
Cooling efficiency	3
Air changes per hour	3 ACH
Minimum outside air flow per person	0.00944 cfm
Occupancy	Residential (3 beds/2 baths)
Solar distribution	Full interior and exterior with reflections
Shadow calculation frequency	30
Shadow calculation overlap	15,000
Roofs	R-value 20
Walls	R-value 11.4
Floor	Concrete
Window	0.38 Btu/Hr.ft^2. °F
Visual transmittance	0.90
Solar heat gain coefficient	0.44
Window–wall ratio	15% total F25 B25 L25 R25
Air conditioner	SEER 13
Furnace	Gas, 78% AFUE
Ducts	15% Leakage, R-value 6

Table 5.2 **Baseline template for a mid-rise four-story apartment considered a commercial building type compliant with ASHRAE 90.1 – 2004. Courtesy of UNL student Bradley Wissmueller.**

	Commercial baseline settings	
Project type	Midrise apartment	
Location	Helena, MT	
Climate zone	6A	
Aspect ratio	L/W	2.7
Building size	GSF	33,744
Number of floors	4	10 foot floor to floor height
	Width and length based on SF, floors, and aspect ratio	x = 55.897 y = 150.92
Occupants	Total occupants	80
Thermal zones	Apartments	Total area of each apartment: 947.224 SF
Shape	Rectangle	Rectangle
Site	Orientation	0 degrees north
Window–wall ratio	15%	
Exterior walls	Construction type	Steel frame
	Wall composition	0.4 in. stucco, 5/8 in. gypsum wall board, wall insulation, 5/8 in. gypsum wall board

(Continued)

Table 5.2 **(Cont.)**

	Commercial baseline settings	
	R-value	2.75 m^2 × k/w = 15.604 Fahrenheit hour/Btu (th)
Roof	Construction type	Insulation entirely above deck
	Roof composition	Built-up roof: roof membrane, roof insulation, metal decking
	R-value	2.85 = 16.17 Fahrenheit hour/Btu (th)
Windows	U-factor	3.81 (w/m^2 × K) = 0.67 Btu/h × ft^2 × °F
	SHGC	0.39
	North and south dimensions	273 SF
	East and west dimensions	109.5 SF
Floor	Type/construction	Mass floor, 4 in slab w/carpet
Infiltration	Air leakage	Infiltration in perimeter zones only: .016 in wc (4 pa), in office, 25% when ventilation on
HVAC	Heating	Always on (electric), zonal: split into individual units for each apartment
	Heating efficiency	0.80
	Size	Autosized
	Water heater	SWHSys1 water heater (0.003785 m^3 tank volume), natural gas, 82.2222 max temperature limit
	Cooling COP	3.67
	Cooling set point	80.1 °F
	Heating set point	68.5 °F
Gains	Lights	0.36 in apartments, 1.0 in office, 0.5 in corridor
	Electric plug-ins	0.5 in apartments, 1.2 in office
Fans	Total efficiency	0.53625
	Motor efficiency	0.825
	Fan max flow rate average	0.28 m^3/second = 0.626 cfm/ft^2

Created for simulation using E+, the commercial reference buildings and their outputs come directly from this particular BEM program. As such, using any program other than E+ will require translating the information into the new software. This task can be challenging when converting units or identifying the proper material or system to use. Without E+ knowledge about how it codes and reports data, understanding, reading, and transferring the data into your BEM program can be an arduous task.

The prototypes summarize typical buildings and help define each building's square footage, shape, window–wall ratio (WWR), envelope and fenestration U factors, system types, and operational performance. Along with data about these prototypical buildings, the simulation results provide information for all the building end uses. One can input this information about the building into the BEM model and then compare the simulation results against those from the prototype. This quality control measure can ensure that all the necessary information is correct. Following

the definition of the BEM, it is possible for this prototype to act as a proxy early in the design process.

This stand-in for your building project, type, and site location can greatly assist with setting early goals. The prototypical proxies can help identify various design strategies for reducing energy when no established design yet exists. The prototypical building may be effective in testing early design modifications to the building, materials, system efficiencies, and system types. By testing various proportions, R-values, and U-factors for different building elements early in design, the proxy can help define what might have the most impact on energy efficiency. However, these models are not meant to act as energy performance targets, used for certifications, nor are they intended to represent energy use in any particular building; they are merely hypothetical idealized models meeting minimum requirements.

Contextual Baseline

Recently the U.S. DOE commissioned Lawrence Berkeley National Labs to develop a far-reaching visual search database of existing buildings called the Building Performance Database (BPD).[4] This database allows you to view a range of different building types and energy performance targets, quickly understanding how your goals stack up against other buildings in the database.

Different from the code-compliant baseline discussed above, using the BPD one can draw a sample comparison from the as-built buildings in the database. Instead of comparing a building with itself, using this data source helps you compare your building with others at a local, regional, or national scale. Research experience reveals that the better the quality and quantity of the sample, the more accurately the results represent reality. Therefore, comparing the design of the building with itself, as in the code-compliant baseline, is less useful than comparing it with a larger sample of as-built buildings.

Depending on your project type, use, size, and climate, the goal is to find a decent and reliable match to forecast your project's energy performance. Using the BPD, you can view a sample of buildings from across the U.S., filtering them to fit what you are looking for. National energy benchmarking and reporting of existing buildings' energy use will continually enhance this sample, increasing its robustness and reliability. This online tool has a variety of statistical methods for comparing your project with many others, helping decision makers identify energy targets and set goals (see Figure 5.3).

Another advantage is that the BPD contains information related to the systems used and represents newer buildings than those from the 2003 CBECS. According to their website, the BPD combines, cleanses, and anonymizes data collected by federal, state, and local governments, utilities, energy-efficiency programs, building owners, and private companies, and makes it available to the public.[5] It is vital that the buildings represented form an accurate and reliable sample, as this

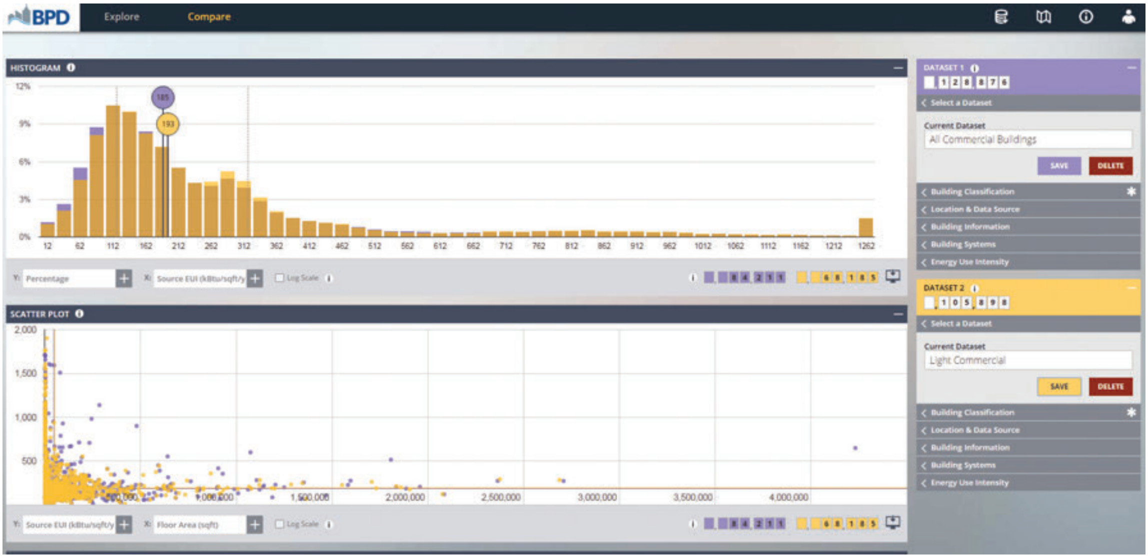

Figure 5.3 **Example dataset from the Building Performance Database.**

affects whether they can be trusted as representative of a data source. Yet, the online tool is the largest database of its kind, capable of comparing your building with many others. This type of comparison is highly valuable for designers wishing to either demonstrate the building's context and performance level, or push the performance boundary to a higher level. However, at this point, forecasting information from a comparable building of similar use and climate is not necessarily easy, given the limited number of buildings you may find in your region.

Summarizing the Baseline

A baseline model establishes an early understanding of your building's energy use. There are three types of baseline model. First is the typical 90.1 code-compliant baseline for self-referential comparison. Second is the use of a proxy baseline model to evaluate strategies for your building type and location. Third is the contextual baseline comparison using national-scale building data to pinpoint projects of similar type and location. Though not an exhaustive list of baseline methods, they do represent the ways forward to defining your starting point for using BEM.

Now that we have begun our road trip by defining our baseline, let us review where this leads to build on your BEM.

Building a Goal-Setting Model

To calibrate design expectations with a goal for energy performance, you can begin with the end in mind. You might find this a bit challenging, but with an integrated

team and early project scoping, the energy-saving conversations will begin the project. For example, to meet the 2030 Challenge carbon reduction goals requires use of the CBECS median building type to benchmark carbon emissions. While the baseline model uses an understandable starting point to measure energy reductions, establishing an actual goal forecasts where the building design could end.

A goal-setting model is not a design exercise; it defines the theoretical minimum energy performance upfront. Doing so helps the integrated team understand where they should focus their expertise to reduce energy use in the building. There may be a variety of goals evaluated, such as a percentage below the baseline, achieving net-zero energy with or without using renewable energy, or carbon neutrality, or setting an annual energy use per unit of measure target.

Since a goal is set at the beginning of a project, very little information exists about the design—perhaps only the program and square footage. Evaluating the specific impacts of elements such as daylighting and HVAC systems is less important than the overall whole-building picture. However, since this is a theoretical exercise, testing a range of possibilities helps outline the energy target for a building. The goal-setting model identifies what is technically feasible with today's technology to achieve energy conservation.[6]

The modeler begins the goal-setting process with the definition of a baseline model, often based on ASHRAE 90.1. He or she then verifies the model against the range of known building performance metrics, from their own body of work, the CBECS median, or the BPD. Using this baseline, the modeler can test various design assumptions about the building to evaluate energy savings. Examples of whole-building aspects to evaluate include increasing and reducing the building size by a minimal percentage, adjusting heating and cooling set points, changing the outside-air requirements, and prioritizing design strategies with the greatest energy-saving impact. In other words, the process defines the local or global sensitivity of your project's many design elements, promoting those that have significant impact and demoting those that have minimal effect on energy savings. Alongside global building items are issues of lighting, envelope, glazing, shading, passive heating and cooling, thermal mass, and daylighting. Following the evaluation of these items' impact on energy savings, a modeler should seek synergies and combinations of energy conservation measures.

By comparing the two types of models (Figure 5.4), the baseline vs. the goal-setting model, you can see that the baseline is about understanding the building as a typical entity and identifying the common energy load profiles and needs, whereas the goal-setting model involves a building's theoretical minimum energy-use potential. Beginners to BEM may not be well suited to jumping into a goal-setting model without understanding the specific reality of the inputs—for instance, while setting the building ventilation rate to zero would indeed have an impact on energy performance, this is not permissible by code, since the people inside need fresh air. Therefore, a modeler should carefully vet their model and assumptions against the code and known design practices.

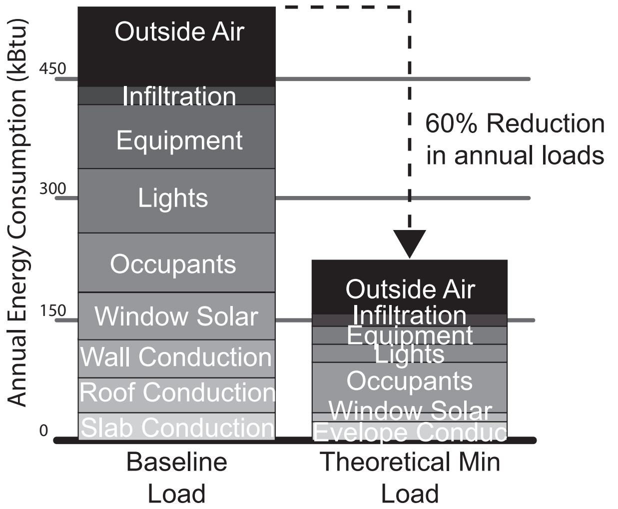

Figure 5.4 **Baseline model (left) and goal-setting model (right). Adapted from Kendra Tupper and Caroline Fluhrer, "Energy Modeling at Each Design Phase: Strategies to Minimize Design Energy Use" (IBPSA-USA, 2010).**

A goal-setting model has several other advantages besides identifying the design target. As a measuring stick throughout the entire building design, use of the goal-setting model can gauge whether it is reaching the intended goal. It can also be used to budget the energy use of different parts of the building, such as plug loads and lighting power density (LPD) to inform the specification of equipment. This defines the daylighting needs and electrical lighting systems to reach the allotted energy budget. Finally, a goal-setting model begs the team to ask an open-ended list of "How might we. . .?" questions to approach the problem. Finding the goal to achieve coincides with setting the energy performance target for a specific building type and climate.

Design Target

In 2003, and most recently in 2013,[7] the Energy Information Agency (EIA) completed the CBECS.[8] Funded by a national mandate, this information solicited data from a large segment of the national building stock. You can use this data as a starting point to locate buildings by type and square footage. Additional information includes climate zone and energy intensities per building type. The AIA uses the 2003 CBECS building data as a benchmark in its 2030 Commitment being the measuring stick for achieving carbon neutrality. Together, the data allows you to uncover an energy target to inform your design objectives.

Setting a straightforward energy performance target uses the Environmental Protection Agency's (EPA) target finder9 on Energy Star's Portfolio Manager, which requires a few initial inputs for building a benchmark target for comparison: gross square footage, project location, operational hours, number of workers and computers, amount of space heated and cooled, and an estimate of your design performance goal.

Table 5.5 **Metrics comparison of a 30,000 sq. ft. office design target to the median property. LEEDv4 EAc1 requires optimized energy performance of a minimum Energy Star rating of 75.**

Metric	*Design target*	*Median property*
Energy Star score (1–100)	75	50
Source EUI (kBtu/ft²)	154.4	208.8
Site EUI (kBtu/ft²)	69.8	94.4
Source energy use (kBtu)	4,632,926.8	6,264,000.0
Site energy use (kBtu)	2,093,586.0	2,832,000.0
Energy cost ($)	34,252.77	46,333.82
Total GHG emissions (metric tons CO_2e)	302.9	409.8

It is similar to the metrics comparison in Table 5.5. Using the EPA's target finder helps uncover your goal and provides a solid benchmark for achieving energy savings beyond the median or regional/national average building of a similar type.

Absent from the target, however, is the projection of how to get there, as spelled out in a goal-setting model. Using a design target informs the team of where they need to aim to meet the project energy goals. From here, the building design can begin to iterate ideas about how best to reach the design target informing the goal-setting model.

Evaluating the BEM Output

Now that you have run your simulations for the baseline and/or goal-setting model, you have defined your energy-saving design trajectory—whether you know it or not the path ahead is there. However, to follow this path most effectively, it is crucial to understand what the energy data reveals. BEM tools produce many numbers. The results can be used in two ways. First, understanding what uses energy, diagnosing the model; and second, to show differences between design alternatives through comparative analysis.

Diagnosing the BEM

Since it is possible to change many aspects of the BEM, knowing what can change helps identify the effect this change has on energy use. However, when considering changes, several questions arise: What are the cause and effect of energy use that can help us to understand how our building behaves? What building elements affect changes in energy performance? If we see a change in energy use, can we pinpoint where it occurs and determine whether it is related to the windows, walls, roof, or floor? When in doubt, change only one thing at a time. For example, if we modify all the U-factors between formal building iterations, there is no basis for

comparison and we do not know whether it is the formal change or the U-factor that resulted in the outcomes.

There are two types of variables to understand: First, the dynamic building components related to non-design-dependent variables such as lights, number of occupants, equipment, and infiltration. These items are not design-specific, but material-, construction-, and technology-dependent, so regardless of the building shape or the number of windows, the outputs from these categories will seldom change. The BEM understands these outputs based on the fixed numbers input by the user; therefore, the outputs come out fixed as well. For instance, to change the heat gain from occupants, the only thing you can do is change the number of occupants or their schedule. Heat gain from occupants is not a design-dependent variable.

The second type, design-dependent variables, are often the static building components related to conduction, solar, and ventilation. These components include the number and type of windows, the materiality of the walls, the building orientation, and the design of shading devices. Essentially, design-dependent variables change how the building relates to the exterior climate—primarily to the sun. Being dependent, changing the design therefore changes the variable's energy performance. For the example below in Figure 5.7, changing the amount of glazing on the building façade would reduce or increase the heat gain by solar energy. Changing the material properties of the glass or the walls would affect envelope conduction.

Using BEM helps designers understand the impact of non-design- and/or design-dependent variables. By reading the simulation results (and with a little experience), designers can quickly diagnose a particular focus for design changes to conserve energy. The next step is to review some of the common outputs, with further discussion on diagnosing design issues and comparative analysis of design alternatives.

Understanding the BEM Output

Interpretation of the BEM by the architect or engineer diagnoses how the design performs in order to improve energy performance. To achieve this diagnosis it is necessary to understand the thermal behavior of the building. Without going into too much building physics detail, heat is transferred by radiation, conduction, or convection. Energy moves through the body of a material by waves, from contact with another material, or via a medium (commonly air). The first law of thermodynamics states that energy can be neither created nor destroyed; therefore, energy exists in equilibrium. Take, for example, the sun's radiant energy: this energy either enters the building directly (solar gain), or hits the roof and walls and turns into conductive heat gains. Combine this with the exterior temperature, and the transfer of energy becomes either a heat gain or loss through the building envelope

depending on whether it is day or night, summer or winter. Therefore, analysis and interpretation of the heat gain or loss results rely on understanding how design elements affect the building's heating and cooling loads.

Depending on your model, using baseline or goal-setting will frame how you view the results. A baseline model merely tells you how the building is consuming energy, but its visual output will help you identify where you can look to save energy. Results from a goal-setting model identify what is working and why a particular strategy may save energy.

Analysis of your building using BEM begins to diagnose design's effect on energy use. There are two ways to utilize BEM: First, during the process of design to explore early considerations, such as program, building geometry, and material compositions; and second, during the fine-tuning of a more tangible building design. The latter is the more understood method, so subsequent chapters of this book focus on the former. Diagnostics of either method are similar and utilize the same results; however, what one tests may vary.

In order from bigger picture to finer grain, the following sections describe what to look at within the BEM outputs to determine where to focus design efforts. This list does not show all the outputs possible from BEM tools, but those common and helpful in diagnosing energy use.

Total Energy Use

Common energy metrics produced by BEM software are the annual energy use or consumption, which is a combination of heating and cooling loads, lighting, and equipment. Sometimes the annual energy use is broken down into electric and natural gas usage and combined to produce total energy use. The total energy use represents all energy uses from different fuel types and reflects any energy production from on-site renewable sources. One single number representing this is energy usage intensity (EUI). EUI is a common metric used to report energy consumption as the total energy use per building square foot per year. Because the denominator relates to the building's square footage, this metric is highly specific and can only compare a building with itself or with buildings similar in size. EUI, however, is a common and easily understood measure due to its simplicity:

EUI = Total energy use kWh or MMBtu / Total building gross m^2 or ft^2 / year

In addition to a project's energy-use metrics, energy costs are another common output. Using local tariffs and utility rates produces annual energy costs, which again can be broken down into gas and electric costs. Costs are a valuable metric for tracking the savings one might achieve with particular design choices, though you should be aware that if the simulation is wrong, the costs are as well. For the purposes of this book, we do not report costs because our work is theoretical

and represents no real built scenario. Additionally, costs are variable depending on location—a kilowatt-hour costs much more in California than it does in Nebraska, or almost anywhere else. Therefore, cost metrics have little meaning related to the examples presented in this book.

As noted above, energy use and costs most commonly come from gas and electricity, though both fuel sources use different types of quantitative metrics. Gas is measured in therms and electricity is measured in watts, while measurements of energy are denoted as Btus or joules. While this is not necessarily at the forefront of our minds early in design, it is nonetheless important to understand these metrics and keep them constant. How you initially report results could control how you continue tracking a project through design, construction, and operations. Comparing a kilowatt-hour with a kBtu is not possible without translation, so it is important to make the correct choice at the beginning and to keep your outputs consistent from there. The BEM tools may report different numbers as well, so it may suit you best to base your energy units on the BEM tool defaults.

Furthermore, other types of outputs are possible beyond the high-level reporting reviewed. BEM tools can output the specific items that contribute to heating and cooling loads, both those that are producing heat and those that are losing heat. Examples include infiltration, number of occupants, lights, equipment, windows (solar), walls/roof/floor (conduction), and ventilation. Since a BEM uses hourly weather data, viewing simulation results as hourly outputs is also possible, depending on whether or not your BEM tool allows this high level of detail. Outputs with more detail enable different levels of analysis for each day, week, month, season, or year depending on the specific question or period you wish to use.

Monthly Energy Consumption

What is using energy in your building? The monthly energy consumption data shown in a chart or output will tell us what items and in what month energy consumption occurs (Figure 5.6). The primary consumers of energy are lighting, cooling, and heating, with the secondary consumers being appliances, hot water, fans, and others, depending on the BEM tool. Examining this output should inform you of what the largest consumers are and in what months this consumption happens, and therefore where reducing energy use has the most impact. While you can also view the annual energy consumption, this is only a lump sum number. This number does not tell us much, but seeing the monthly report can give us a better picture of when this consumption occurs.

Monthly energy consumption data helps show us where the energy in a building is used. One key takeaway from Figure 5.6 is that monthly energy consumption figures can show us when, over the course of the year, heating and cooling loads are the largest or smallest. For instance, if cooling is the largest overall energy consumer from May through September, then focusing on passively

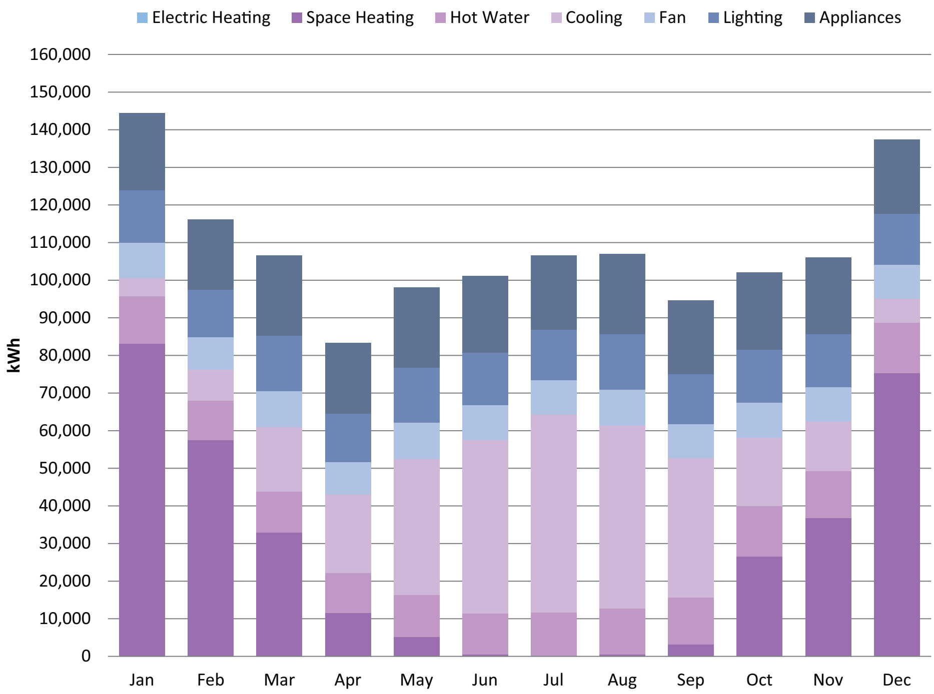

Figure 5.6 **Monthly energy consumption.**

cooling the building during this period with natural ventilation or earth coupling might be an effective approach to reducing energy use.

Heat Gains

Our building will gain heat (Figure 5.7) from several fixed sources: equipment, lights, and people. These are non-design-dependent and typically do not change in a BEM. Next come the heat sources related to infiltration and ventilation; again,

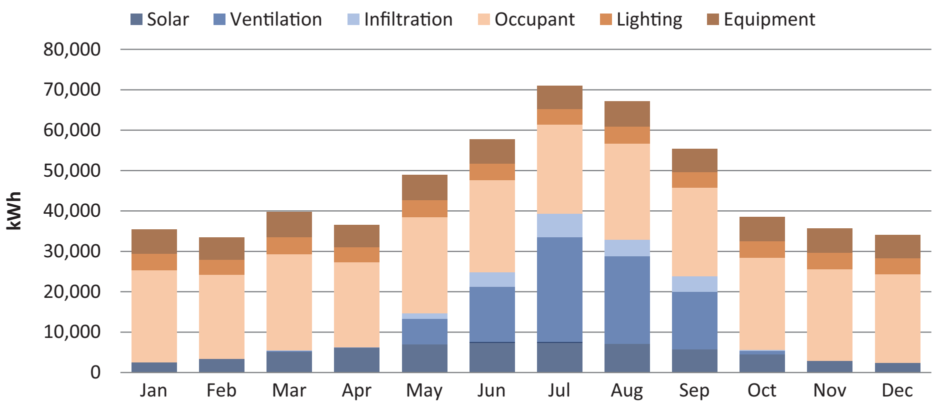

Figure 5.7 **Monthly heat gains.**

these will not change much unless changes are made to the construction, materials, or building systems. Outside of these sources, the two main heat gains to watch for are the building's conduction and solar gains. Heat gains from conduction relate to the amount of the building exposed to the sun. A more compact building with less surface area, in theory, should have fewer conductive gains. Solar gains are those that come from the sun passing through windows, quantifying the amount of heat gained in the interior space. Changing the amount, location, and materiality of the glazing will change this number. Reducing heat gains increases heating loads and decreases cooling loads.

Heat Loss

Similar to the gains described above, losses (Figure 5.8) occur through infiltration, ventilation, and conduction. Here again the losses by infiltration and ventilation should be controlled by keeping the construction, materials, and system performance constant, whereas conductive losses will change based on the exposure of the building envelope to the external climate. The amount of wall area here is likely to have the greatest effect on changes to the amount of heat loss. The greater the wall area, the more heat lost. In addition, the wall material, whether transparent or opaque, will also affect the amount of heat loss.

The heat loss shown in Figure 5.8 is quite different from the gains example. The heat loss diagnosis will depend on each element's share of the overall loss amount: for instance, if conduction has the largest share year-round, then focusing your design efforts on eliminating thermal bridging and increasing the overall exterior

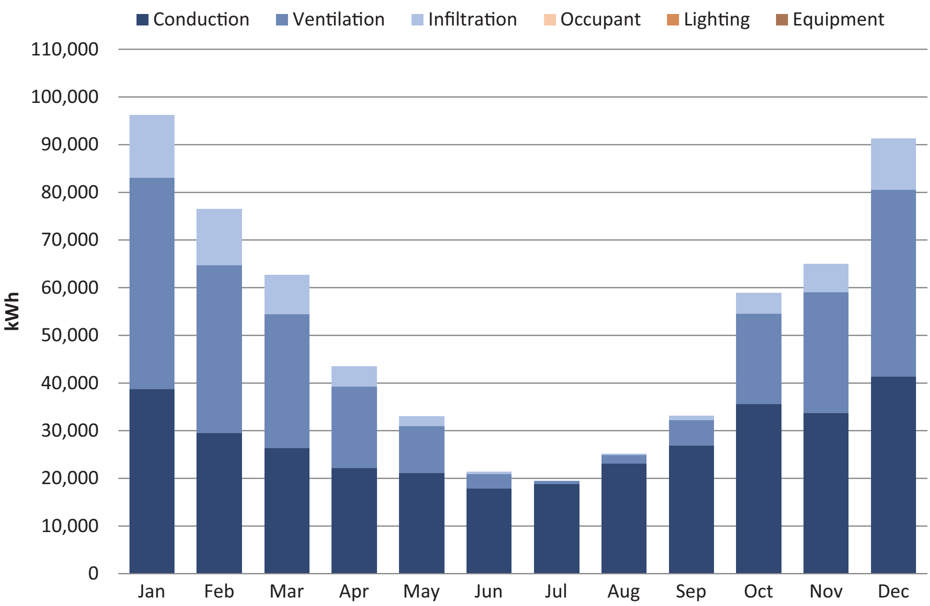

Figure 5.8 **Monthly heat losses.**

U-value may help to reduce these losses. Working to reduce heat loss keeps more heat within the building, decreasing heating loads and possibly increasing cooling loads.

Conductive Loss or Gains

Another report worth evaluating is the conductive heat gains and losses through building envelope elements (Figure 5.9). Often referred to as fabric conduction loss or gain, this chart shows how much heat loss or gain occurs through the windows, walls, roof, and floor. As in any pie chart, the overall 100 percent will not change, but each element's contribution or piece of the pie can change. Therefore, the largest pie piece tells us which building element contributes the most to gains or losses and holds the greatest potential energy savings. BEM tools report fabric gains related to heat transfer toward the interior; depending on your climate heat gains may primarily affect cooling loads, while the fabric heat losses affect the heating loads.

Once you know the gain or loss result you can see which building element contributes to it the most. Examining the heat gains and losses in depth and zooming into the fabric to identify what factors contribute to these changes is an excellent way to diagnose your building performance. Once you have a whole picture of each design iteration or difference explored using BEM, you can view the performance metrics alongside the design iterations.

Heating and Cooling Loads

A particular favorite task of mine is to look at a line graph of both the heating and cooling loads for the building and in relation to specific elements such as the WWR

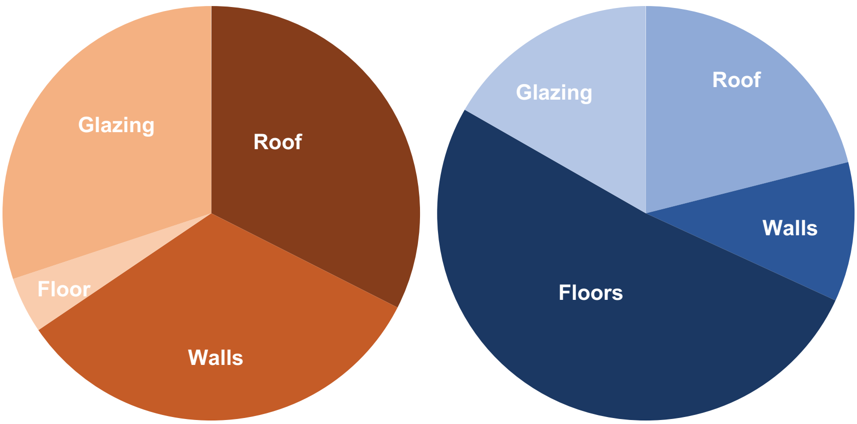

Figure 5.9 **Pie charts of the conductive gains (left) and conductive losses (right).**

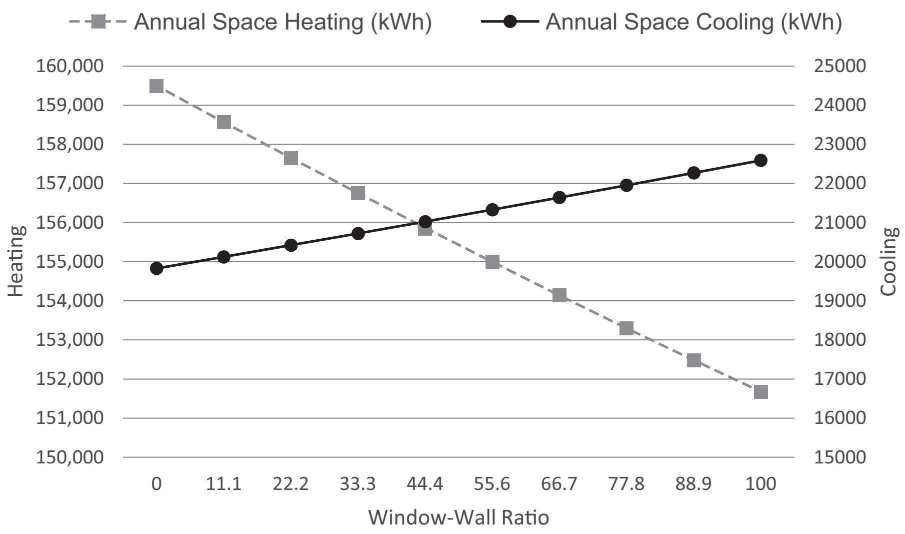

Figure 5.10 **Annual heating and cooling loads.**

(Figure 5.10). Again, the point is to diagnose how energy flows change in the building based on design-dependent variables. Often, design changes may not appear to have much impact on the total building's annual energy use; this may be because you decreased the heating loads and increased the cooling loads. Looking at why this might happen can help you identify strategies, for instance, to reduce heating and keep cooling the same, therefore saving more energy overall. In extreme hot or cold climates, one of these modes is typically dominant. Reducing one mode may increase the other, but it is the magnitude of this change to overall energy conservation that should be considered.

As exemplified in Figure 5.10, the changing WWR results in opposite effects on the heating and cooling loads. However, in this climate and for this building type the heating loads are more substantial and more significantly affect the annual energy consumption.

Diagnostic Approach

Following the BEM simulations that control for variations in aspects of the BEM not important to our building design decision, we can sort through the data to gain a clear picture of building performance. Understanding how the building behaves in a climate helps the designer and team operate with more confidence when making decisions. Diagnosing the BEM explains the impact certain building elements have, and why.

Parsing simulation data to achieve a proper diagnosis is fundamental. As noted previously, using monthly energy consumption is a better method of diagnosing what the building is doing than using the annual energy consumption

number. Monthly reporting shows how the climate and building interface, and which particular systems operate to maintain internal comfort.

Following charts of monthly energy consumption, heat gains, and heat losses the modeler can compare the resulting trends and patterns of the design options. For example, as we iteratively change the amount of glazing in a building, these three charts will change as well. Depending on the climate and building type, both the consumption numbers will go up or down and the gains or losses will shift between walls and windows.

Diagnostic analysis is formative in understanding how the design is operating related to energy performance, and then feeds back into the design process. As such, for the most impact the BEM should run concurrently with the sketching of the building design. Perhaps this is something design architects can do as they model their buildings, or perhaps the energy modelers or analysts can tag-team the analysis of iterations shortly following. Whichever method you choose, using BEM upfront, early in the process, can help tie performance goals to design approaches and improve your skills and your results, and the energy performance of your building design.

Comparative Analysis

To compare overall design options or different designs, the big-picture results, the annual energy consumption and EUI, are most effective. Comparing side-by-side results of which design elements have the largest impact on overall energy use is another approach to presenting the conclusions of your analysis and design exercise (see Figure 5.14). Alternatively, you could complete a formative and/or summative comparison at key milestones during a project's design. The formative comparison may show the causes and effects to provide a clear rationale for design results from an energy perspective. Following this, completing summative comparisons may show how to design specific building elements to achieve energy conservation, as shown in Figure 5.11.

Comparing a design with itself, the summative comparison shares concluding results of a design activity, whereas the formative comparison acts as an in-process report describing which direction the team is heading in. In a formative comparison, the feedback connects back into the design and further influences the outcomes, such as the design of shading devices described in Figure 6.23. At major project milestones, a summative comparison demonstrates building performance at the conclusion of the design activity.

In addition to the overall EUI comparison in Figure 5.11, it may be helpful to report the total energy use, annual heating, and cooling results. Different design options may behave differently depending on the comparison, and seeing how one design requires more heating versus less cooling could open up an entirely different design path.

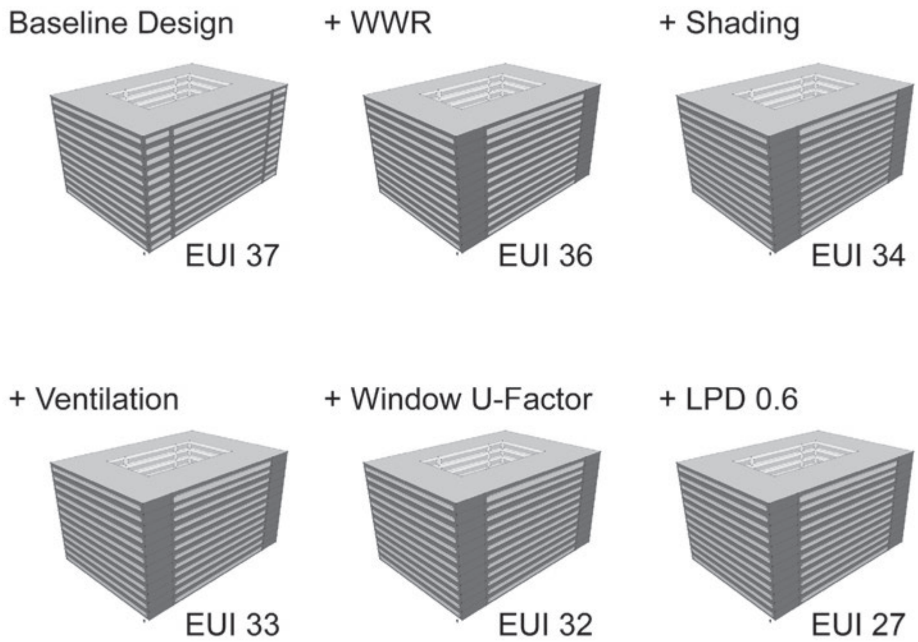

Figure 5.11 **Summative comparisons of energy conservation measures' energy reduction from baseline.**

Leveraging the Goal-Setting Model

Next, the goal-setting model will represent your desired energy savings target. In this case, your inputs were the starting point for your roadmap. To achieve the target EUI, you have reduced your LPD, added shading devices, modified the HVAC system, added photovoltaics, maximized your R-values for the walls and roofs, and generally figured out that you don't have money in your budget to reach your energy goal. In all honesty, operating a model intelligently is not about throwing whatever you think will work at a problem; as discussed in the climate chapter, a sound design begins with an assessment of the design strategies available in your particular climate for your particular building type. A goal-setting model built on these features suited to your climate holds the most promise.

Highlighting the end-use energy in a goal-setting model defines an energy budget for the building. Since the basis of this model might be previous projects, known information about daylighting design, or other best practices for systems performance, the project team can agree to budget out the energy uses for the fixed equipment, lights, and systems based on the BEM. During design, using this information helps compare the design with expected outcomes to see if things are on track.

To conserve energy, there are non-design-dependent steps designers can take. However, a sound goal-setting model should evaluate both the non-design- and the design-dependent variables. In the next few chapters we discuss in more

detail how to evaluate essential passive solar design variables with BEM to determine their energy impacts.

Often, customizing the data is necessary to make your point clear; default outputs usually do not look very good and will not necessarily tell the story you want. Therefore, developing a clear, legible, visually appealing template for the data is important, along with evaluating what you want to say with the results. In addition, choosing a clear analysis method can benefit our understanding of results and inform our analysis of the simulations.

Analysis Methods

BEM evaluates a whole building's operational energy. A BEM can simulate any number of building elements and their energy use, and a robust simulation gives an architect, energy modeler, or engineer a complete picture of where a building consumes energy.

Discrete elements are individual aspects of a building, such as a wall or window. Using BEM to evaluate changes in an element requires simulating the whole building's operational energy use in relation to changes to these discrete elements, often called an ECM. Often we do not look at single, discrete elements on their own—their energy relationship to the whole building is what needs to be evaluated.

How do you do this, you might ask? Well, there is a hard way and an easier way. The hard way requires statistical evaluations using Morris or Monte Carlo methodologies—both of which are robust, but time-consuming. An easier approach is to establish a BEM that systematically combines the best of the discrete elements. Easier does not suggest simple or faster, however. Simulating a lot of information takes time and the more detailed and complex the data is to simulate, the more time it takes. Methods for evaluating the discrete elements rely on the power of computation through such approaches as one-at-a-time modeling, brute-force modeling (BFM), genetic algorithms, and parametric models, all of which use BEM as part of their methodology.[10]

One-at-a-time modeling is precisely what the name says. You look at one thing and only that one thing until you have completed your analysis. One-at-a-time modeling is ideal for complex items such as our geometric sensitivity analysis, where controlling the item's variability for the analysis related to the rest of the building's complexity helps produce accurate results. Many energy modeling equations and methods likely started as simple one-at-a-time calculations until the architect, engineer, or researcher gained enough confidence in the validity of the results. For example, in 1963 Victor Olgyay senior completed a single-day analysis of various residential building forms in which he examined a very limited range, in large part because he had to do all the math by hand before the invention of the modern calculator. Today, in contrast to Olgyay's smaller sample, our one-at-a-time simulation with BEM can examine every hour of every day of the year.

Sequential search technique is a linear method: From your list of possible options, you go through and test each one until either you find your goal or your list runs out. Commonly used within computer science, an algorithm or routine is set up to search the list for a match or result that meets the specified criteria. Within the auspices of BEM, evaluations achieve a specific goal and therefore search a wide list of potential options until they locate the desired result.

BFM is exactly what you might expect: brutal. BFM evaluates every possible combination of elements until it has exhausted all the possibilities, and perhaps your patience with it. While not necessarily ideal, BFM can be helpful when you have no real idea where to begin or lack the time to program other approaches. Some BEM tools have routines set up to complete BFM simulations, allowing you to select a large set of possible items to simulate and simply click Go. BEopt software by NREL, for example, is loaded with common residential construction materials and systems. This tool comes with a parametric analysis feature that allows you to choose any set of ranges and complete a BFM of up to 10,000 different possibilities. Before trying this, make sure your CPU is up to it!

Not all BFMs need be that brutal, however. If you have completed the analysis of several individual items, you might be able to limit the evaluation to a key set of the most promising ones by using a local sensitivity analysis (also known by several other names, including simply a sensitivity analysis). While there are different types of analyses, the use of this term often refers to just one discrete item's sensitivity. Green Building Studio, for example, completes a BFM of preloaded options when uploading a new simulation, reviewing the potential energy-saving features of the building and showing you the results of the BFM's local sensitivity. Another example is Sefaira, where for an individual element you can choose to run a response curve for a range of ten different increments. Sefaira strategies within various project concepts enable users to see the impact of one, two, or more items on the baseline energy use. Here, grouping specific elements together begins to expand the analysis from one local item's sensitivity to more global impacts on energy use.

Genetic algorithms (GAs) are another way to simplify the potentially large dataset of design options into a manageable method for analysis. Rather than modeling all possibilities, a genetic algorithm randomly selects a potential option and moves it forward. Based on the idea of natural selection and survival of the fittest, a genetic algorithm does not bother to simulate those options that are unlikely to have much impact, focusing instead on the fittest options for analysis. In this way, GAs move much more quickly through a larger dataset to find the optimal and most energy-efficient solution.

More common than GAs are parametric models to evaluate energy impacts. The first of these is an algorithmic model predicated on an "if this, then that" ruleset programmed into a design program. The model can take time to set

up, but it can simulate a large dataset quite efficiently. While algorithmic models are not as automatic as a GA, their advantage is that the designer remains more in control of how the results will be determined. With experience, the model can be robust, and modified to produce different results to evaluate energy when coupled with or included within a BEM program.

This approach, often called a parametric model (PM) for simplicity, programs a relationship or routine with a specific logic to reach a solution—for example, when you need to determine a specific rectangular area for a building footprint, but are not sure of the optimal aspect ratio for energy use. Parametrically controlling the range of all possible length-to-width ratios then simulated using a BEM solves this problem. After it is complete, the results could show all possible combinations or simply identify the best based on the programmed goal.

Analytical methods common in BEM tools from BFM, GA, and PM allow design decisions based on the local sensitivity of individual design elements or combinations of elements within an entire building system. Alternatively, a global sensitivity analysis describes how important a particular element is, based on how many other elements it affects or that affect it. Our review of these methods has hopefully enticed you to read further on to Chapter 7, where we discuss how to set up some of the PMs to evaluate different aspects of a building's energy use.

Before jumping into energy modeling and analyzing the data produced by the simulations, you must first begin with a starting point. Beginning with a baseline establishes what you might simulate and why, and defining where to begin helps establish which analytical tools and methods will work best.

Determining Impact

The truncated examples above show limited information from the BEM and are specific to monthly energy consumption, heat gains, and heat losses. Larger-scale information such as the annual energy consumption total and EUI provide a summative understanding of energy performance in a succinct number. This global view is not necessarily helpful in diagnosing the design, but is best at showing how significant the impact of various building elements can be to the overall picture, allowing comparison with your baseline or goal. For example, understanding how significant a role building orientation plays in energy consumption should inform the siting of a building. If building orientation plays a significant role, then we should pay careful attention to it, whereas if it is not significant for whatever reason, the team can move on to other, more important energy-saving strategies. Prioritization of which building elements have the greatest energy impact is another advantage of starting with a baseline model. Two approaches discussed here focus on understanding an element's sensitivity by using a statistical indexing method and a simple linear graph of several points.

Sensitivity Analysis

Testing performance ranges for specific design elements helps determine their energy performance and importance. Using a local sensitivity analysis can show the individual impact on the overall building's energy use.[11] Various BEM tools have this analysis built in as either a function or a feature. A sensitivity index (SI) works by choosing two different settings for an element and then using BEM to simulate each, producing a high/low range of energy performance (commonly based on the annual energy performance or EUI number). Once the BEM has produced the range for all the elements, evaluating each one using the equation below creates a numerical value. Sort the numbers from high to low; those with a higher number have more variation, or importance, for a building's energy performance. Identifying the sensitivity can help diagnose the impact an individual item might have on the overall building's energy performance. The simple sensitivity equation takes the maximum value minus the minimum value divided by the maximum and multiplied by 100, best written as shown in Equation 5.1:

$$SI = (Emax - Emin \ / \ Emax) \times 100 \quad (5.1)$$

The SI creates a numerical expression from a range of data. Table 5.12 summarizes the performance of 12 differently shaped office buildings in each of the six key climate zones in the U.S. Sorting the maximum, median, and minimum building energy consumption expresses the range for each city, followed by the SI. The SI tells us which city's climate resulted in the largest difference (and the largest SI number) between the energy performance of the 12 buildings—in this case, Miami. Miami's climate had the highest SI number in Table 5.12; it also had the greatest variation of difference across the 12 building shapes simulated; this outcome indicates that for a small office building, its form is more important in Miami than it is in Chicago. If we investigate building form further, we could eliminate, say, the worst building from the pool, thus decreasing the SI number.

Many aspects of a building's performance could benefit from using sensitivity indices. For a building with fixed building geometry, an SI helps compare

Table 5.12 **Sensitivity index showing the maximum, median, and minimum values of buildings' performance within six climate zones, summarized as a single SI number.**

	Minneapolis (6a)	*Chicago (5a)*	*Baltimore (4a)*	*San Francisco (3c)*	*Phoenix (2b)*	*Miami (1a)*
Max.	2,027,643.38	1,838,065.00	1,721,953.98	1,032,635.69	2,316,749.13	2,721,246.03
Median	1,675,549.01	1,747,017.02	1,614,378.50	950,244.63	1,913,166.06	1,998,465.62
Min.	1,613,112.34	1,665,307.20	1,502,230.62	838,319.86	1,779,963.66	1,925,005.38
SI	20.44	9.40	12.76	18.82	23.17	29.26

ranges for U-factors across the envelope to identify which one might have the most impact. For instance, in Miami the roof might be the building's most significant element, whereas for the same building in Minneapolis the significant element might be the walls. Using SI can help identify the individual significance of these features.

Data Visualization

In some cases, a numerical SI might not communicate the best or create the most understandable representation of the data. Often, a simple graph visualizing the data can explain as much and more about a specific element's impact on energy performance. For example, Figure 5.13 shows a small house's annual energy consumption costs for each foot change in overhang depth. This type of representation is usually far more effective than explaining how sensitive a change in overhang depth can be. We can also see that an overhang beyond three feet in depth has a minimal impact on energy consumption.

Figure 5.13 also shows more detail about the overhang beyond the limits of the SI equation. If we were to have run a simulation of just the zero- and five-foot overhang depth, we would not have been able to see that the three-foot overhang was optimal, nor would our simulation have shown that after the overhang reached four feet, it began to act against the building's overall energy performance by blocking out desired winter heat gains.

Both the SI and the line graph have their place in determining the impact of individual building elements on energy performance, and assessing when to use each is crucial to making design decisions. In the two cases shown above, using the SI on larger aggregate data from many different simulations reveals impacts of basic building geometry, whereas the line graph compares the energy costs of

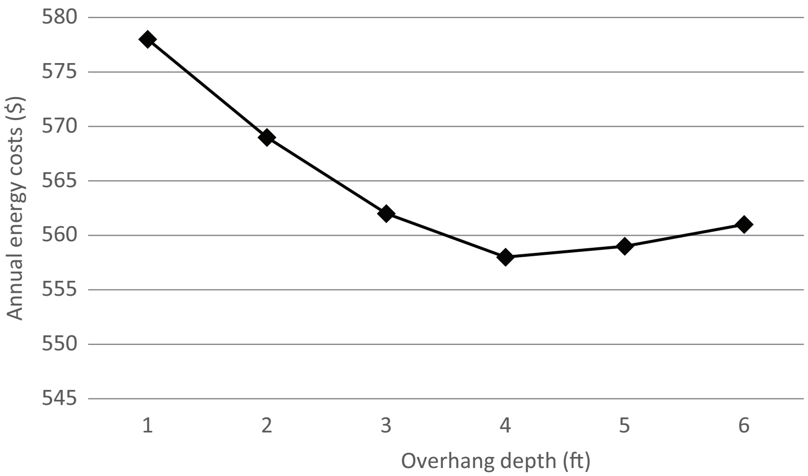

Figure 5.13
Energy cost versus overhang depth in a small residential project.

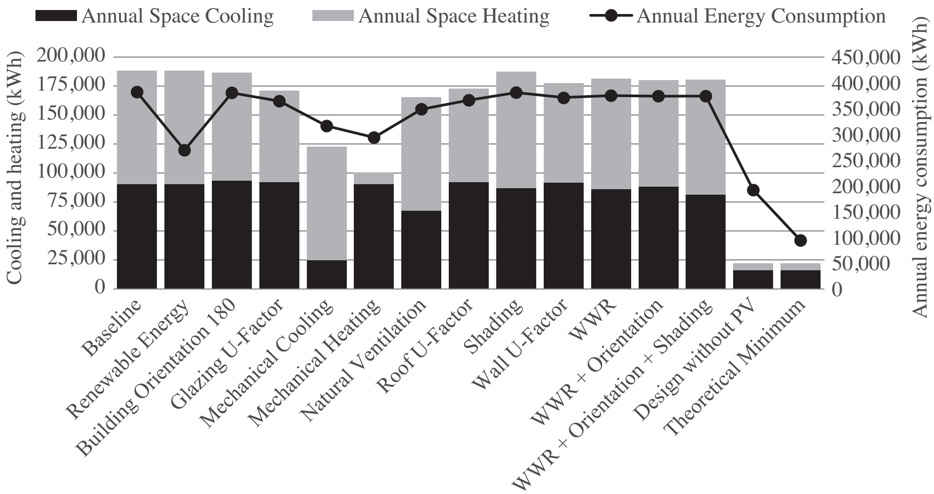

Figure 5.14
Discrete element evaluation of annual energy loads, heating, and cooling. Individual elements compared with baseline (far left) and theoretical min (far right).

five different points. In other words, when working on smaller, discrete examples, using basic methods to convey the information could prove best. Alternatively, a chart with hundreds of points is less clear than a single number or bar chart for each discrete element, as shown in Figure 5.14.

Where to Go from Here

Now that you have a goal in mind and basic baseline simulation results for your building, you can design as you would for any other project, taking the information that you have and figuring out your basic design. During the energy design process,[12] you will uncover questions about some of the fundamental elements (discussed next) that energy modeling is well suited to answer. Using your design target, the energy model can help you build your own baseline. Testing each iteration you explore during the design process can help you to understand basics like the impact of a thin versus a compact form, or a series of buildings versus one large one. Designing with energy in mind is best evaluated with building energy modeling.

Exercise: Create Your Own Target

Go to the EPA's target finder (https://portfoliomanager.energystar.gov/pm/targetFinder) and, using some key building metrics, replicate Table 5.2 to establish an energy target for the building. Common metrics needed for the target finder, depending on the building's use, are:

- project location;
- building function, hours of operation, number of occupants;

- equipment, number of computers, appliances, or cooking equipment (defaults can be used);
- gross square footage;
- fuel mix for the state (defaults can be used).

Input the information required, then choose either an Energy Star rating or a percentage reduction from the national median (target percentage). Once submitted, the report will inform you of the site and source energy targets for your specific project type, square footage, and location. Congratulations on your first step to setting an energy savings goal!

Notes

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3 U.S. DOE, "Building Energy Codes Program: Commercial Prototype Building Models," www.energycodes.gov/commercial-prototype-building-models.
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9 U.S. EPA, "EPA's Energy Star Target Finder," www.energystar.gov/buildings/service-providers/design/step-step-process/evaluate-target/epa%E2%80%99s-target-finder-calculator.
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6 Passive Solar BEM

Architects should be wary of those who exaggerate the impact of passive solar design. We often hear presentations that aggressively tout the energy savings of passive solar design strategies—though without understanding the specific context, climate, building type, and other details, these statements can be misleading. Additionally, after years of simulating almost any design feature we could think of, we have discovered that there is no single catch-all design strategy that will save massive amounts of energy. Instead, saving energy involves the craft and artful combination of as many design and material strategies as the project can hold—in other words, the synthesis of multiple measures into a whole. The modern monikers of *less is more* or *form follows function* do not necessarily suit what the modern masters intended, given the growth of heating, cooling, electrical, and water systems in buildings. With all of this new technology, buildings today are anything but less.

Instead, you might adopt a contemporary perspective of *more is less*: Perhaps, in a building, more active systems result in less energy. Research exists demonstrating how adding more renewable energy systems achieves zero-energy buildings and developments,[1] and alternatively, one could advocate for less architecture or building to reduce energy—a less is less approach, as seen in the popular trends of tiny houses that do more with less. Whether making more or less, neither is necessarily more energy-efficient; in fact, your choice may be less efficient depending on how you view its use of energy. The purpose of this chapter is to elaborate on multiple energy conservation measures (ECMs), with a focus on passive solar design approaches.

Passive solar design is the use of architecture and climate to provide heating, cooling, and ventilation without mechanical (active) systems. Another way of describing passive solar design is the use of free resources provided by the sun, wind, and earth. Without the intent to design the architecture to integrate and embrace these free resources (a technique known as bioclimatic design), the building must rely on active mechanical systems to provide the heating, cooling, and ventilation. Formulating the architectural response to climate often begins with geometric design considerations.

Geometric Design Considerations

Form does not follow function—instead, the form of a climate-adapted building is a function of energy performance, known as performance-based design. Here, form follows performance. How so?

Orientation (Figure 6.1) has long been a primary passive solar design strategy, and ranks among the most researched; however, it is not as sensitive as building geometry, such as the building's aspect ratio or height (what we call stacking). Aspect ratio (Figure 6.2) is the two-dimensional relationship between a building's length and width, while stacking (Figure 6.3) is a building's vertical proportion and the number of floors, which increases as the building grows in height. These are the three main building blocks that architects use to design a building's form and delineate its two- and three-dimensional envelope shape.

BUILDING ORIENTATION
MAXIMIZE SOUTHERN EXPOSURE & MINIMIZE WESTERN

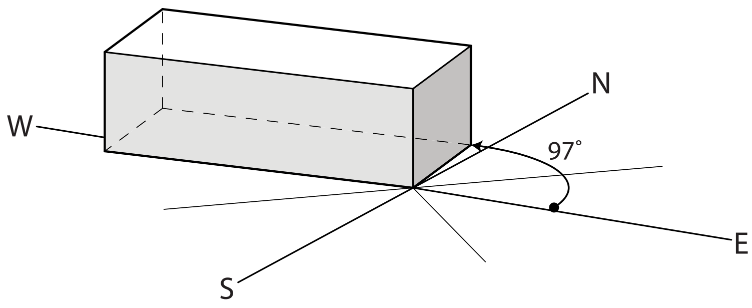

Figure 6.1
Orientation diagram showing the optimal east to west degree rotation for climate zone 5 to maximize southern exposure and minimize western solar radiation.

ASPECT RATIO
BUILDING LENGTH x WIDTH

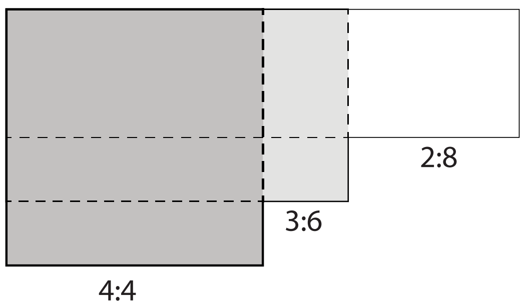

Figure 6.2
Aspect ratio showing the relationship between a building's length and width while maintaining total floor area.

STACKING
VERTICAL PROPORTION OR COMPACTNESS

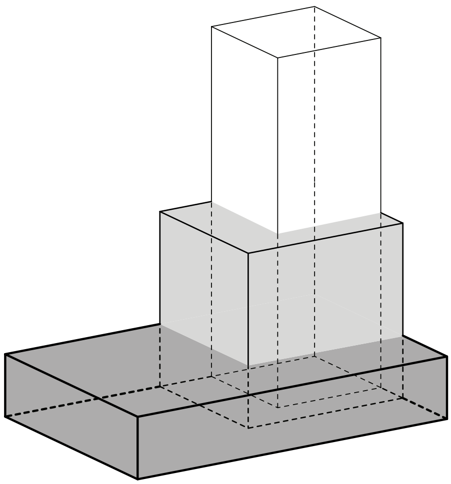

Figure 6.3
Stacking diagram of a building's vertical proportion maintaining internal volume.

Geometric properties are sensitive not only individually, but when evaluated together. Combining orientation, aspect ratio, and stacking defines the shape effect. Proper orientation should go hand in hand with both aspect ratio and stacking. Buildings take on many different shapes, and evaluating their effect on energy use is a study more complicated than merely evaluating a single geometric principle.

Some common building geometries include the letter shapes L, T, H, U, and others. As explained by Thomas Hootman, "the creation of narrow shaped floor plates with fingered wings and courtyard spaces allows for daylight and natural ventilation,"[2] and such floor plates are ideal for passive solar design. Looking at the architectural composition of a building form based on these simple shapes is one way to begin.

Combining the metrics of aspect ratio and stacking for a fixed square footage and floor-to-floor height results in an array of different building forms, as seen in Figure 6.4. These forms represent different potential designs, and depending on your climate and use type, the energy performance of these building geometries will vary widely.

Another geometric design method is shape aggregation—piecing together similar or dissimilar shapes into a massing. As the name implies, one can imagine shape aggregation as the architect putting different types of blocks together to compose the building's overall geometry. While shape effect looks at one mass, a building's massing is the assimilation of many forms, whether similar or different (Figure 6.5). Evaluating a building's massing is often necessary in larger

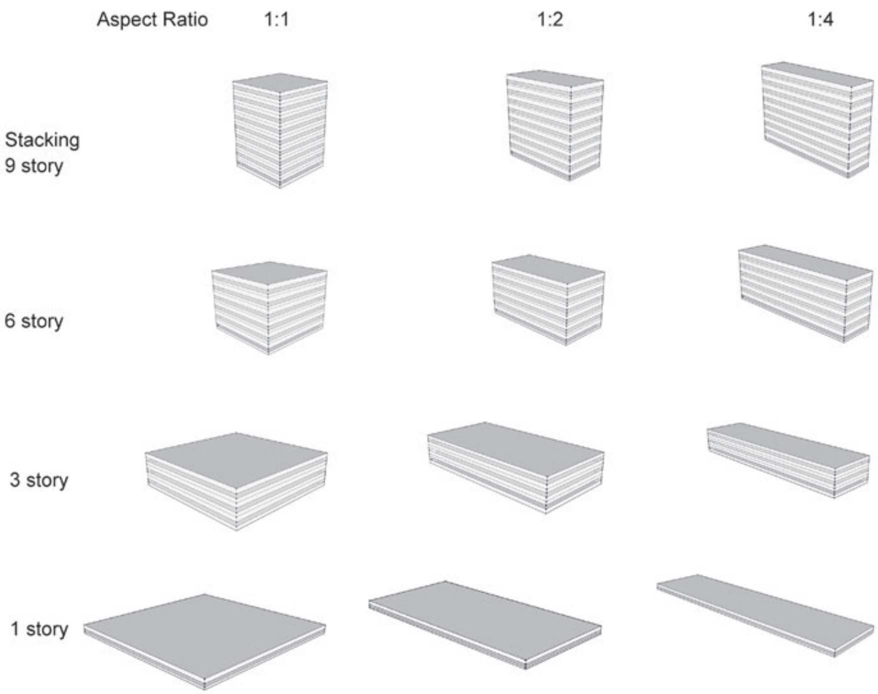

Figure 6.4
Conceptual massing of 12 different combinations of aspect ratio and stacking.

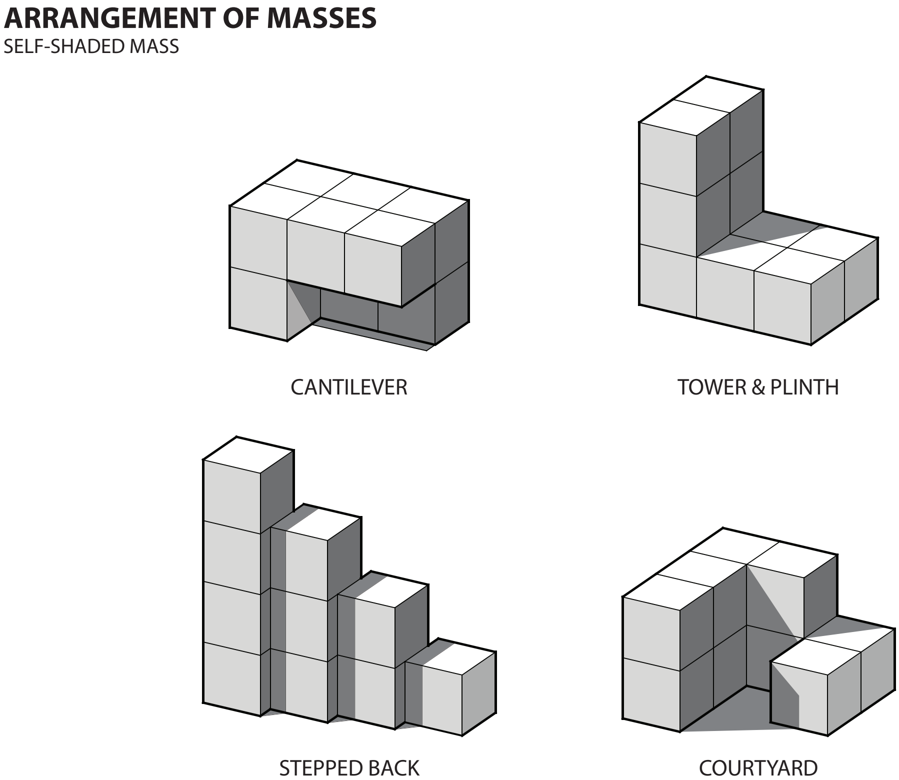

Figure 6.5
Examples of shape aggregation or massing of a building's form.

buildings, complexes, and campuses—for example, in a hospital, or in part of an addition to an existing building.

The composite mass affects the building's energy use either by shading some parts or by maximizing solar access in other parts. The two approaches of shape and mass influence other design decisions, such as the location of glazing or the fenestration design. Climate-adaptable strategies explore the relationship between the building's overall mass and the sun (often referred to as the solar envelope[3]). This relationship has been the subject of much research and has influenced both policies in certain areas and the design of entire cities, such as the planned Masdar city project in Abu Dhabi. In colder climates, shaping the solar envelope and building mass allows sunlight penetration and maximizes the uptake of the sun's radiation for heating. Alternatively, as in Masdar, hot climates lead to a shape and massing of buildings and urban forms that reduce the sun's penetration, helping to cool the city's narrow streets.

While the early design of a building remains fluid as the building evolves through the various stages of design understanding, its geometric sensitivity to energy use is critical. As discussed, there are ranges of geometric issues that affect how a building form works as a function of energy. The orientation, aspect ratio, stacking, shape effect, mass, and scale of the building's geometry all play into a complex orchestration of energy use. During discrete analysis with BEM, these individual elements interact in complex, formal relationships that affect energy use.

Measuring Building Geometry

There are several metrics used to measure a building's geometric form and relate it to energy performance. Research shows that geometry-based indices only correlate with a building's thermal performance according to specific climate regions and building types;[4] therefore, it is paramount to evaluate energy use with BEM during design to evaluate how modifications to a building's geometry can affect its energy use. The geometric measures below are helpful in making case-by-case comparisons between different iterations of a building design; however, when comparing different building types and climates, you likely are comparing rocks with apples. Following this summary is the literature review discussing the research.

1. **Compactness index** (C) is a measure of the building's internal volume-to-exterior surface area (V/S), with the higher number being the most compact. It is the inverse of the shape coefficient.
2. **Shape coefficient** (Cf) is the ratio of surface area to volume (S/V), where (S) is the sum of all surface areas in contact with the outside air and the building's enclosed internal volume (V).

3. **Relative compactness** (RC) is the ratio of a building's compactness index (Ci) to the compactness index of a reference building, with the reference building being the more compact.
4. **Window-to-wall ratio** (WWR).
5. **Window-to-floor ratio** (WFR).
6. **Window-to-surface ratio** (WSR).
7. **Floor area to enclosure** (F/E).
8. **Exterior wall to floor area** (EW/F).
9. **South exposure coefficient** (Cs) is the southern-facing wall-to-volume ratio (Ss/V).
10. **Shape factor** or **aspect ratio** (AR) is the ratio of the building's length to depth.
11. **Above-grade surface area** (S) is the surface area of the building, walls, and roof.
12. **Building internal volume** (V) is the building volume enclosed by the ground floor, walls, and roof.

The above metrics typically quantify building geometry and come from a wide range of literature. The most common metric is building compactness. Compactness is the building's volume divided by its exterior surface area (V/S).[5] While early building literature considers S to include the exterior area in contact with the ground, more recent discussions omit this from the value of S, limiting it to only the above-ground exterior surface area. This measurement is not necessarily an absolute, but you should define it for your project. If you have a large amount of below-ground building area, you can either quantify this area as part of S or break the surface area into two different values for that above ground and that below, we suggest S_a and S_b.

The inverse of compactness is shape coefficient describing the total building's surface area over the building's overall volume (S/V).[6] When evaluating a building's geometry using these metrics, it is common to keep the volume constant: A 3,000 m^3 building's energy use is very different than that of a 300,000 m^3 one, though they may have the same compactness. For instance, in Figure 6.6, where the building surface area is minimal, the stacking of a building that maintains its volume is most compact at the mid-range.

Another version of the shape coefficient as proposed by Jon Straube also eliminates the ground-floor area from compactness, suggesting that floor area/ enclosure (F/E) is more accurate than the compactness proposed by Gratia and Herde. This not only makes logical sense, it is consistent with the research and a building's differing thermal performance with the ground versus through its walls or roof. Straube also eliminates the total interior volume from his considerations and prioritizes only the floor area, arguing that in most buildings the interior volume value is misleading due to the size of the plenum spaces that alter the interior conditioned space volume.[7] Adding to these metrics, Thomas Hootman, in his

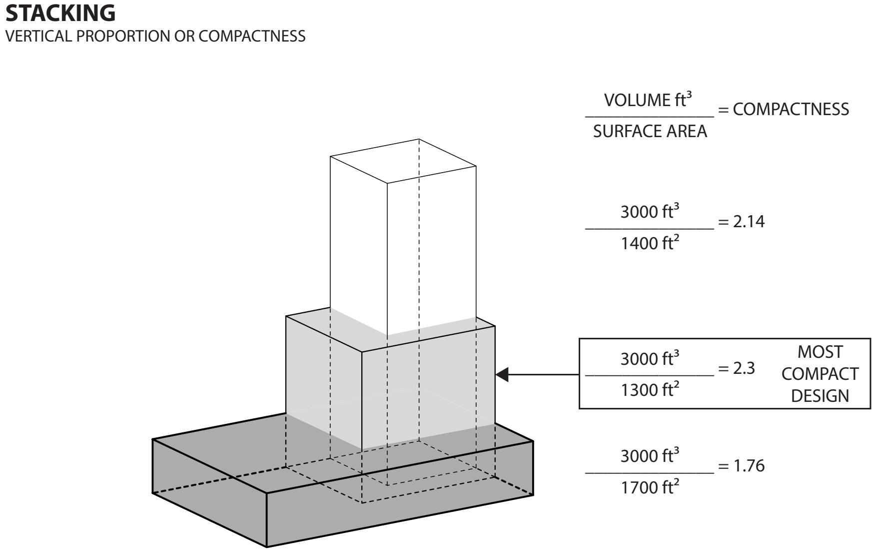

Figure 6.6 **Example of how stacking affects a building's compactness index, showing the most compact form versus two other options.**

book *Zero Energy Commercial Buildings*, suggests that the total exterior wall area divided by the floor area (EW/F) is ideal for measuring a building's passive solar design potential[8] while also using the shape coefficient (S/V), the inverse of the compactness index.

To summarize the building volume-based measures, you have compactness as the volume/surface area of building (V/S), the floor area/enclosure (F/E), the exposed wall/floor area (EW/F), and the surface area/volume (S/V), all of which highlight different geometric volumetric measurements of various building forms. Other two-dimensional and related metrics include the building's quantifying shape factor/aspect ratio (the building's ratio of length to depth, L/D), along with the building's overall height (H), surface area (S), and volume (V).

Finally, research by Eugénio Rodrigues quantifies a clear and comprehensive list of variables, called geometric indices,[9] which includes those highlighted above and the WWR, which is usually the percentage of glazing compared with the total wall area. Additionally, the WFR is familiar to architects primarily because building codes require a minimal amount of windows compared with the floor area for natural lighting and ventilation. Other ratios on the geometric indices list are the WSR and the southern exposure coefficient (Cs), which relate exclusively to different ways of measuring the surface of the building itself. To compare the building's energy use with its geometry, it may be helpful to utilize these measurements depending on what questions you need answered. Table 6.7 summarizes the geometric indices shown for the conceptual masses in Figure 6.4.

This summary of building research studies and geometric indices allows one to correlate a building's thermal performance (its energy use) with the geometric building metrics. Architects examining different climate zones and building

Table 6.7 **Summary of building geometric indicies for each office shown in Figure 6.4.**

	V/S	*F/E*	*EW/F*	*S/V*	*Ss/V*	*Ratio*	*Height*	*S*	*Volume*	*Rc*
1	5.44	0.83	0.21	0.60	0.00	1.00	1.00	117,810	640,332	0.38
2	11.68	1.44	0.36	0.28	0.01	1.00	3.00	54,530	636,804	0.82
3	14.22	1.48	0.51	0.23	0.01	1.00	6.00	44,744	636,192	1.00
4	14.19	1.36	0.62	0.23	0.01	1.00	9.00	45,122	640,332	1.00
5	5.41	0.82	0.22	0.61	0.01	2.00	1.00	119,392	645,504	0.38
6	11.43	1.40	0.38	0.29	0.01	2.00	3.00	55,648	636,192	0.80
7	13.72	1.41	0.54	0.24	0.02	2.00	6.00	46,417	636,804	0.96
8	13.59	1.30	0.66	0.24	0.02	2.00	9.00	47,197	641,574	0.96
9	5.31	0.79	0.26	0.62	0.01	4.00	1.00	121,312	644,496	0.37
10	10.74	1.27	0.45	0.31	0.02	4.00	3.00	59,318	636,804	0.76
11	12.35	1.24	0.64	0.27	0.02	4.00	6.00	51,512	636,192	0.87
12	9.81	0.90	1.00	0.33	0.03	4.00	9.00	65,296	640,332	0.79

shapes can benefit from understanding which specific measurement might work for the building type in the specific climate. For robust analysis results, simulations of hundreds of different building shapes are necessary, though not everyone has time to find the correlation between geometry and energy use within a particular climate. There are enough differences in each particular building's type, program composition, and system that no one element can serve as a catch-all for a designer to specifically focus on; designers should instead seek balance between the most crucial elements for that particular building's needs.

Which particular piece or pieces do you emphasize to achieve the desired effect? With BEM, architects can test and evaluate iteratively to create a clearer design decision. Our experience is that most often a particular solution is not optimizable (if we may use such a word), meaning there is not necessarily a perfect answer to a problem. Historically, this large solution space for building design has been a challenge. Fortunately, our computational tools today open new doors and opportunities to search this space for an approximate answer that might work.

Geometry across Climates and Building Types

Geometric sensitivity of a building's form varies due to many complicating factors, primarily climate and building type. A specific geometry that might work for a building in Boise, Idaho is not going to perform the same in Athens, Georgia. An evaluation of the climate and passive solar opportunities is critical to reduce energy use when beginning a design in any location. Refer to Chapter 3 for weather data and climate analysis tools for BEM.

As briefly identified above, the geometric measures of a building's form can help in understanding its energy use using BEM. For instance, in colder climates a building's compactness typically relates to the amount of energy required to heat it. A higher compactness number exposes less surface area to the environment,

making the building more efficient to heat. However, a compact building form would have a lower exterior wall to floor ratio or southern exposure coefficient and these are often useful metrics to maximize passive solar heating or daylighting. Therefore, searching for an optimal number in one measure of a building's geometry may exclude the opportunities afforded by others. Balancing discrete with whole-building decisions with your energy goals can overcome this.

A compact building form often helps in cold climates, whereas a less compact building form may help in hot or humid climates. For example, a less compact form (Figure 6.4) has more roof area, decreasing the total envelope's U-factor and increasing the amount of floor coupled to the earth. In a hot climate, this is likely to decrease the building's cooling needs. Shape-based indices such as compactness often demonstrate a strong (or sometimes very strong) negative correlation,[10] meaning that the difference between being less compact and more compact does indeed affect the building's energy use; however, it might not always be affected in the way you predict. For example, if we maintain a building's shape coefficient and make the building taller, the building becomes less compact since we have more wall area and have shrunk the roof by adding more floors within the same volume; this will also increase the EW/F number. Therefore, within an internal-load-dominated building type, such as a large office, this may actually help reduce cooling, since we are increasing the amount of wall area. Another benefit of more wall area is that there are greater opportunities for daylighting the building, further reducing its energy use by moving the loads from internally dominated to more skin dominated.

When considering a building's windows and glazing properties, the common advice is to reduce the amount of glazing on its east and west façades. On these exposures, the sun is far more difficult to control due to its low position in the sky as it rises and sets over the course of a day. Evaluating the various window metrics may yield some help in balancing the thermal loads for a specific climate. Research on the window-based index shows a moderately negative correlation in cold climates for two- and three-level design programs;[11] therefore, in a cold climate, increasing the amount of glass decreases energy use. How so? In residential buildings, increasing the amount of glass will often increase the amount of passive solar heating. Regardless of the geometric indices chosen, however, careful consideration of the thermodynamic relationship of climate and building type will help designers make decisions and build on their BEM.

Building on the BEM

In addition and in response to climate, design decisions related to other building factors such as site selection, program, space layout, window location and size, fenestration design, and material choice can all be evaluated early in and throughout design using BEM. Do not evaluate all of these factors at once! When starting a BEM baseline as discussed in Chapter 5, the following iterative design process

builds on the BEM and helps define with more certainty the design priority for your specific building within the design process. An experienced project architect or manager may identify and prioritize design issues more easily than others. In the absence of a manager's expertise, the design process the book adopts follows MacLeamy's optimal design process curve. By using the curve, a designer using BEM to evaluate key points during design knows when these decisions may occur.

Following the BEM framework, the modeler can evaluate other building factors. Where you might choose to begin is dependent on circumstances and issues specific to the project. Based on the authors' experience and from a review of literature written about BEM in design, the subsequent paragraphs highlight how and when to use BEM during design to assess a building's energy use related to site, program, space layout, WWR, fenestration design, and material choices.

Site Considerations

Site evaluations using BEM will depend in large part on how accurately your model represents the building's context, whether it be rural, suburban, or urban. BEM tools are not well-suited for modeling topography or vegetation due to the geometric complexity of these elements, meaning that exploring alternative methods is necessary for these features. However, in understanding the impact of existing buildings on a particular site, there are numerous opportunities for using BEM. Based on the surrounding buildings and the project location, radiation, shadows, and wind flows are factors in urban areas.

Evaluating one such factor is the relationship between differing formal urban morphologies and solar radiation. Ralph Knowles at USC developed the concept of the solar envelope, explaining how architects can design a building within the urban form to maximize or minimize daylighting within the surrounding environment.[12] Similarly, the solar envelope also could articulate the solar radiation levels within the urban form as a way to select sites or understand the energy impact of urban design decisions. Designers may choose to avoid or embrace aspects of an urban context depending on the type of project. MIT has an urban-modeling plug-in for use in Rhinoceros that explores many energy-related issues of urban design.[13] From MIT and the creators of the BEM tool DIVA, the UMI plug-in allows the testing of different urban form issues.

In any context, understanding the possibilities of different suburban or rural site exposures for sun or wind access is also important when siting and designing bioclimatic buildings. The landform affects how the wind moves and how you choose to shape your building for natural ventilation. In the Hawaii preparatory academy case study discussed in Chapter 8, once the CFD modeling of natural ventilation was complete, design revisions were made to improve the building's passive cooling. In addition, the energy modeling consultants analyzed the larger landform to model wind direction.

Program and Use

Essentially, people give off heat, and our activities while in a building cause our heat levels to fluctuate. Our specific habitation of a building contributes to the internal heat gains and determines the amount of heating and cooling needed. Understanding the type of program and its associated uses allows an estimation of the occupancy heat gain. The age, sex, and other factors of the occupants help to define the amount of heat and moisture (latent heat) we contribute to the internal environment. Occupant density is the number of people in a space determined by the occupancy type and allowable density per code requirements. For instance, our sitting at tables in a restaurant results in a lower overall density (0.7 people/100 ft^2) than an auditorium (12.5 people/100 ft^2),[14] where people sit closely together in many rows of seats. Compare these with a gymnasium (3 people/100 ft^2), where people are not packed as densely as in the auditorium since they are sweating and far more active. These factors influence the amount of sensible and latent heat we contribute to the interior of the space. Sensible heat raises the air temperature, while latent heat contributes water vapor to the air. Their combination determines the total heat gain from occupancy.

Following the occupancy from use and program types is the contribution of electric lighting to the internal heat gain. Lights generate heat as a byproduct of the illumination they provide. The type of light, its illumination level, and its efficiency determine the amount of heat it will produce. The illumination level necessary depends on the type of activity. Specific visual tasks—for instance, drafting on a sheet of paper—will require higher levels of illumination. Illumination is the amount of visible light we see on a surface, measured in foot-candles or lux. While drafting requires higher illuminance levels (50–100 foot-candles), general work environments may only require 20–30 foot-candles on the work surface.

Lighting, plug and process loads, and occupancy comprise the properties for the thermal zones of a layout. These dynamic, non-design-dependent features of program and use determine the LPD, plug loads, and occupancy load settings used in a BEM. Depending on the type of BEM tool used, for the whole building these factors are applied as a single zone or input into each zone of use. Modifying the LPD, plug loads, or occupancy in a BEM can affect both the building's electrical use and its heating and cooling loads.

Program Examples

Investigating a variety of program mixes in a building is useful in understanding how different use types perform. For instance, the example in Figure 6.9 compares the mixed residential and commercial uses in a common building in terms of their contribution to total energy use. Since the energy footprint of commercial buildings

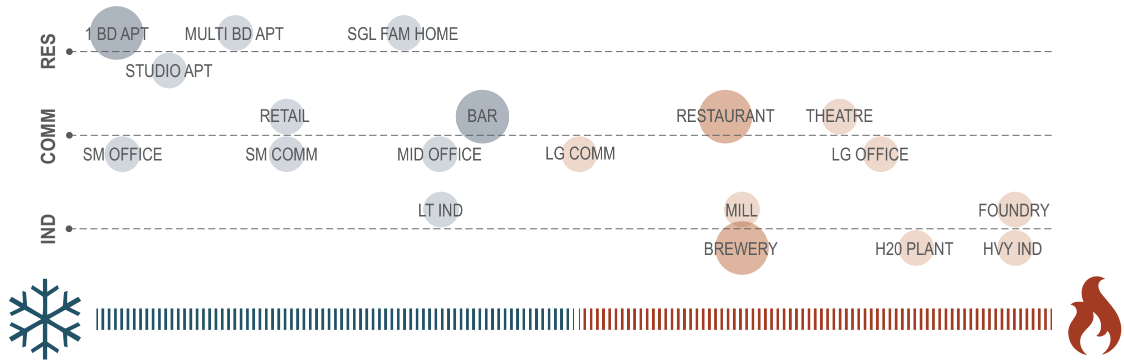

Figure 6.8
Diagram showing a range of building type uses based on internal heat loads. Iconography developed from icons found at https://thenounproject.com. Courtesy of Christopher Rokahr.

is typically larger than that of residential ones, the mixture of the two changes in a non-linear manner. Depending on the project goals, program analysis can assist the design team in deciding the right mixture of uses in a larger multi-use facility.

Another way to think about program mixing is to evaluate internal-load- versus external-load-dominated types. Comparing the dominating mode of operations for building programming can aid the design team in locating spaces or programs in the design accordingly, or in helping the owner identify ideal mixes of occupancies. Figure 6.8 maps out some common program spaces based on their internal heat production.

Finally, somewhere between these two examples is space-by-space energy mapping for large program types, such as healthcare facilities. Completing a

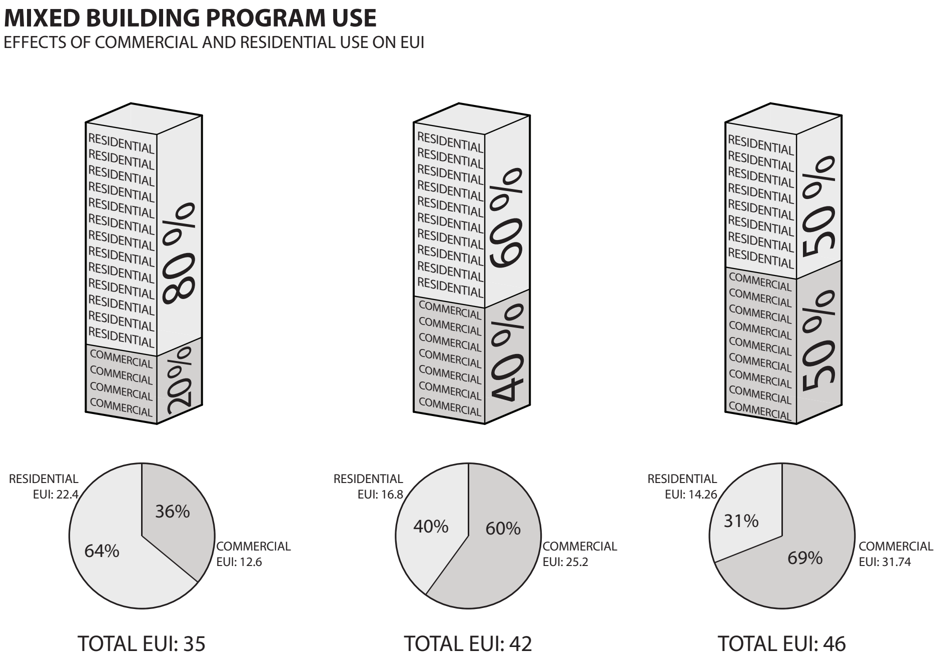

Figure 6.9
Diagram of programmatic mixes of residential and commercial and resulting energy usage intensity (EUI) of three combinations.

space-by-space analysis can help designers locate and distribute spaces or prioritize areas within the building that require more attention. Armed with energy-use information, owners can prioritize different types of services and understand the long-term impacts of high-energy-use areas versus low-energy-use spaces for inclusion in the building design.

These three examples highlight how, even during the pre-design stage of a building project, programming with BEM for different types, sizes, quantities, and adjacencies of spaces and energy considerations can be crucial in maximizing architecture's ability to conserve energy.

Space Layout

Space use decisions made using BEM tools can help designers understand where to locate different rooms and spaces, a process referred to as daylight and thermal zoning, where spaces are located in the floorplan based on their daylighting needs or thermal performance. Many BEM tools can complete daylight analysis to show the quality and amount of daylight within a particular building space, while others can visualize the amount of solar radiation a site or building mass will receive, helping designers locate spaces based on thermal solar needs, or avoid other areas where intense radiation would cause the occupants to overheat.

The interior layout of a floorplan establishes how spaces relate to the amount of sun, light, heat, or cold gained. Layout matters when planning the interior of the building. Whether in space planning for daylight or thermal comfort, how the plan evolves is an essential part of passive design. Measuring space planning energy use is not a typical operation. Some BEM tools are set up for individual thermal zones based on the types of uses identified in the plan and the building's particular thermal needs. However, when completing simulations earlier in design, less space information may be available, and the designer might not know the precise location of different functions within the building plan. Therefore, evaluating the floorplan with BEM early in the design process may not work well, but one can evaluate other important issues to space planning, such as daylight on a generic floor.

Daylighting is a driver of interior space layout—a process referred to as daylight zoning—in many high-performance buildings. Daylight zoning relies on locating spaces that are suited for natural light in the appropriate location. People want to work or live in daylight, and prefer these areas over those lit by electrical lighting. Running simulations to determine the quality and quantity of daylight helps design teams to allocate spaces according to their need for natural light. Two metrics used to identify daylight quality are spatial daylight autonomy (sDA) and annual sunlight exposure (ASE). sDA is a measure of the annual usable daylight in a space, while ASE is a measure of the space's annual exposure to direct sun that can cause glare. Since the simple goal is to maximize sDA and minimize ASE, designing top- and side-lighting to achieve 100 percent sDA would mean

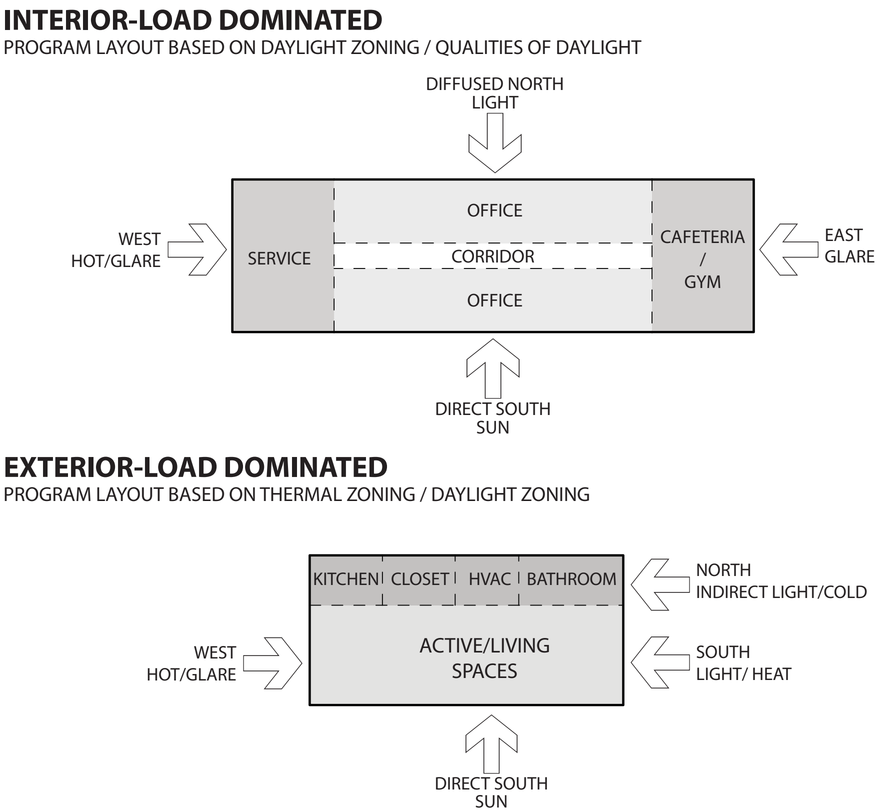

Figure 6.10
Common space layouts for internal-load- and external-load-dominated buildings, which prioritize thermal or daylight zoning.

that the space is engulfed in daylight for all occupied hours over the course of the year. Alternatively, if you had a space that was 100 percent ASE, the space would be flooded with far too much light—great for a greenhouse, but not so much for other activities like working or reading comfortably.

Spatial layout of a building plan based on daylight zoning involves locating rooms and spaces based on the quality of daylight. The most common example is highlighted in Figure 6.10, where main workspaces are stretched along the south and north façades. Along the north façade, diffuse daylight will penetrate, and on the south façade—with proper fenestration—natural daylight can reduce the need for electric lighting. To elaborate more on spatial layout based on daylight, we will later discuss overall fenestration design.

Thermal zoning considers the location of spaces based on heating and cooling needs to take advantage of synergies. This is contextual; for instance, spaces that can be hot may be located near the west elevation, where it matters much less that they heat up during the day. Or spaces that may be colder may be located on the north side of a building, away from the heat of the sun. These ideas are nothing new to the design of architecture. Vitruvius, in his ten books on architecture, elaborates on how to lay out spaces based on the sun:

> We shall next explain how the special purposes of different rooms require different exposures, suited to convenience and to the quarters of the sky. Winter dining rooms and bathrooms should have a southwestern exposure, for the reason that they need the evening light, and also because the setting sun, facing them in all its splendor but with abated heat, lends a gentler warmth to that quarter in the evening. Bedrooms and libraries ought to have eastern exposure, because their purposes require the morning light, and also because books in such libraries will not decay.
>
> Dining rooms for Spring and Autumn to the east; for when the windows face that quarter, the sun, as he goes on his career from over against them to the west, leaves such rooms at the proper temperature at the time when it is customary to use them. Summer dining rooms to the north, because that quarter is not, like the others, burning with heat during the solstice, for the reasons that it is unexposed to the sun's course, and hence it always keeps cool, and makes the use of the rooms both healthy and agreeable. Similarly with picture galleries, embroiderers' work rooms, and painters' studios, in order that the fixed light may permit the colours used in their work to last with qualities unchanged.[15]

The principles behind the logic expressed by Vitruvius involve designing around the sun's seasonal differences. Since Vitruvius lived in Italy, his advice is only applicable for that specific location, but his ideas have inspired other architects throughout the centuries to design for their own bioclimatic locations.

Other strategies beyond the location of rooms are the creation of thermal buffer spaces, which help to mediate between internal and external thermal conditions. We are all familiar with some of these thermal buffer spaces in residential dwellings: crawl spaces, sunrooms, enclosed porches, and others. These spaces, designed and utilized correctly, can buffer the building from hot sun or extreme winter winds. In commercial buildings, a greater range of space complexity requires designers to consider an increased number of thermal needs. Depending on the type of commercial building, datacenters, server rooms, and commercial kitchens can all create more heat than they need. These spaces could be located on the perimeter, along the north or west, where the spaces can cool passively. Alternatively, in colder climates locating these spaces strategically could reduce the building's overall heating needs.

A thermal storage space can store excess heat from higher thermal zones to use at different times of the day or night or in other areas of the building, essentially reusing the heat created by the building operation systems. Thermal storage spaces can also be used to help cool the building passively. Earth-coupled systems such as a labyrinth or earth tube can reduce the temperature of the air as it moves into the building.

To summarize, designing for thermal and daylight needs has long been important to architects over the centuries. Today, our advantage lies in our ability

to simulate with a high degree of accuracy both the amount of available light within spaces and the thermal performance of spaces exposed to the sun. When used together, BEM and other simulation tools help to evaluate the complex aspects of daylighting and other design elements. BEM tools are only beginning to link the use of daylighting to a building's energy performance, as we discuss further in Chapter 7.

Window–Wall Ratio

When designing with BEM, one aspect to evaluate is the amount of glazing on a façade. In a typical BEM, the location of the glazing is not usually as critical as the amount of glazing the various building façades have. Early on in pre-design, this might not be as important as it is during the schematic design (SD) and design development (DD) phases following the definition of spaces, but what is important is evaluating WWR often as the design evolves: it is not necessarily something to analyze once and then set in stone. In addition to inextricably linking the quality and quantity of daylight, WWR (Figure 6.11) intimately relates interior space layout

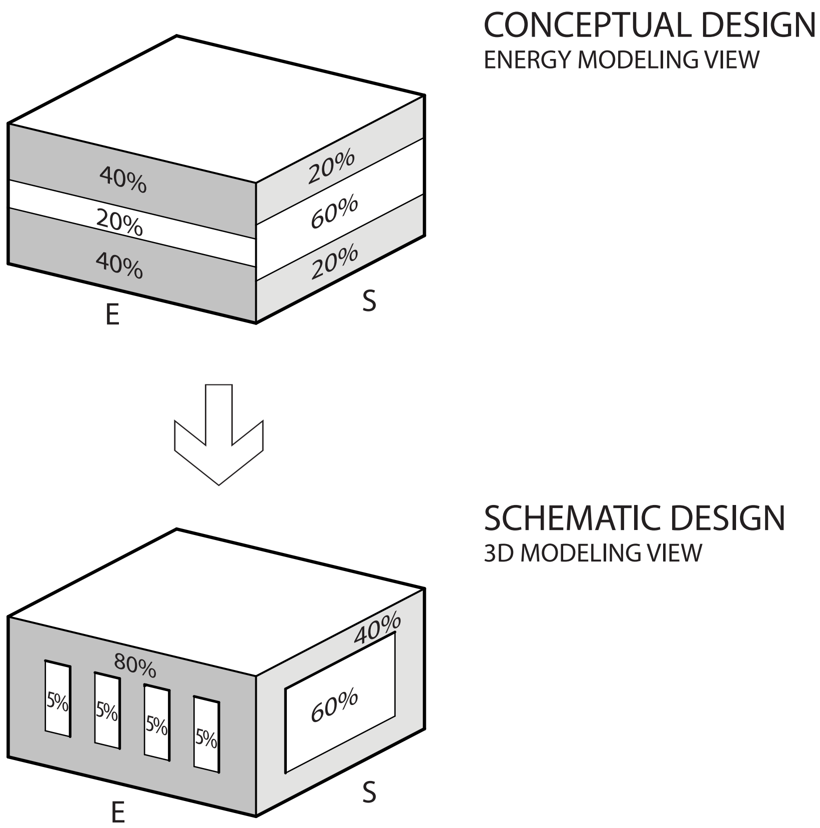

Figure 6.11
Common space Example of how WWR is defined for a building façade related to either the total wall area typical for WWR or as a percentage of the floor area (WFR).

and fenestration design. From our analysis, WWR is one of the most interconnected design elements; in other words, changes in other elements such as the walls or roof will have a large impact on how WWR behaves in relation to energy use.

The type of window, the frame material, and the glass used all affect the amount of solar gain, the sun's affect on the building's heating and cooling loads. Windows either allow sun to pass through or reflect the sun's rays; this amount is a function of the solar heat gain coefficient (SHGC). SHGC is the glazing's efficacy at blocking the sun and is expressed as a number from 0.1 to 1.0. Alongside SHGC is the amount of visible transmittance (VT), the amount of light that passes through the window. VT is not as significant a factor for energy use as SHGC, but considering VT is nonetheless an important qualitative design decision: Installing windows that people can't see out of or that don't let in light would defeat the purpose of having a window.

As an example of the SHGC glazing property, a change in SHGC creates an inverse relationship between the annual space heating and cooling loads. While this may appear to result in no real energy savings in certain climates and building types, in the case of our medium office building located in Miami, Florida, the lower the SHGC, the greater the annual energy use, as Figure 6.12 shows.

In the case of passive solar heating in a colder climate, a lower SHGC decreases the amount of passive solar heat gain that reaches the interior. The same simulation in a different climate results in the graph shown in Figure 6.13. Here, the annual energy consumption is not linear, suggesting an optimal SHGC of 0.4. Similar to the Miami building, the heating and cooling loads have an

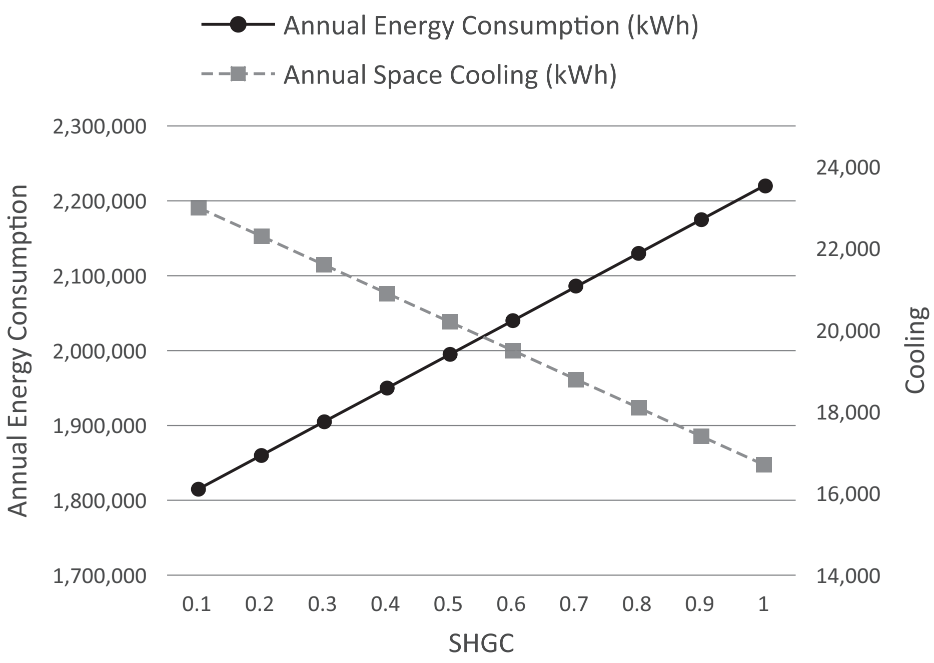

Figure 6.12
Example of SHGC effect on a large office in Miami, Florida showing annual cooling loads (right axis) and annual energy consumption (left axis).

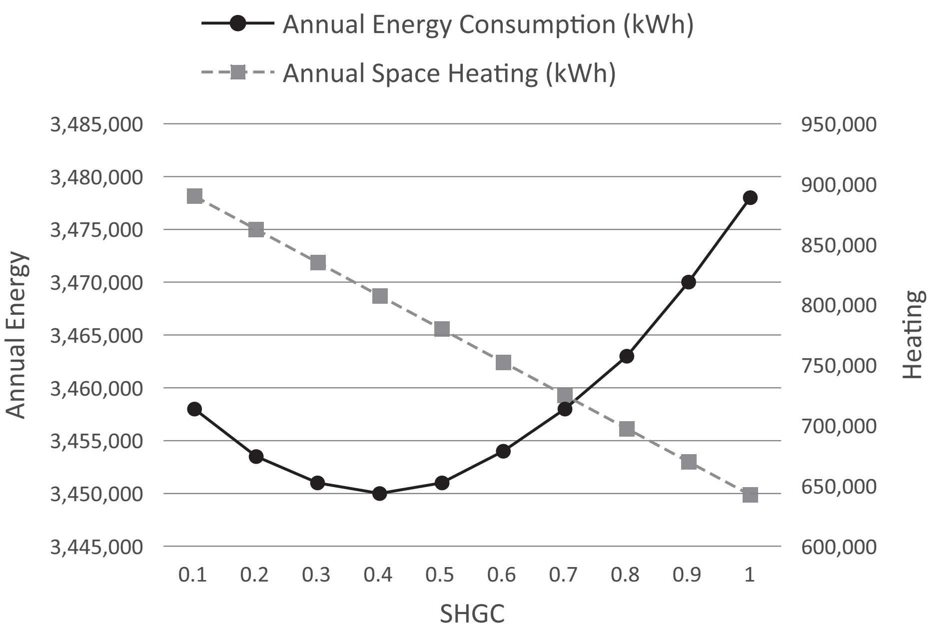

Figure 6.13
Example of SHGC effect on a large office in Burlington, Vermont showing the annual energy consumption (left axis) versus annual space heating (right axis).

inverse relationship, though the effect of passive gains through the windows allows us to make a clearer decision regarding the SHGC value for the windows in this colder climate.

Determining the proper WWR requires that the building architecture and engineering leverage the distribution of glazing and how it is used for lighting, heating, cooling, and ventilation. The general approach is to maximize glazing for daylighting and minimize the glazing for overheating. While this seems like a relatively simple concept, it is actually quite complex. As one increases the glazing to maximize daylight, one is also increasing the amount of heat gained and lost (depending on your climate) through the building envelope. This is because a window is the least thermally efficient element of the building envelope. The other complicating factor is that more glazing introduces more glare into a space, which reduces the overall quality of the specific area.

Solutions to address these complexities involve the strategic use of shading devices both internally and externally, the planned distribution of spaces, and the careful design of the window locations and building form.

Fenestration

The design of fenestration is the thoughtful integration of the windows, both the glass and frame materials, with the building's interior walls and shading devices. There is a seemingly endless variety of combinations of different windows, materials, and possibilities for resolving a building's fenestration; one could locate interior blinds, roller shades, or drapes to coincide with various exterior blinds, awnings,

and overhangs. Devices that are vertical, horizontal, or fixed versus adjustable could be combined into eggcrate-type shades or a specific sun-screen. The overall goal of these combinations is to address the lighting, heating, and cooling issues faced by different building types in different climates (Figure 6.14).

Next, to demonstrate several of these complexities, we simulate a series of fixed exterior shading device types to investigate the effect these systems have on reducing a building's energy use, doing so alongside the daylight performance (Figure 6.24). The common shading devices are vertical, horizontal, egg-crate, and perforated skins, as shown in Table 6.15 and Figure 6.16.

Certain types of buildings with large internal loads should avoid unwanted heat gain from the sun. An ideal strategy is the use of shading devices on windows that still allow daylight and pleasing views. For example, if used in Miami, the brise soleil can shave three percent off the annual energy consumption of the building previously modeled above. The awning, however, is not nearly as effective, and

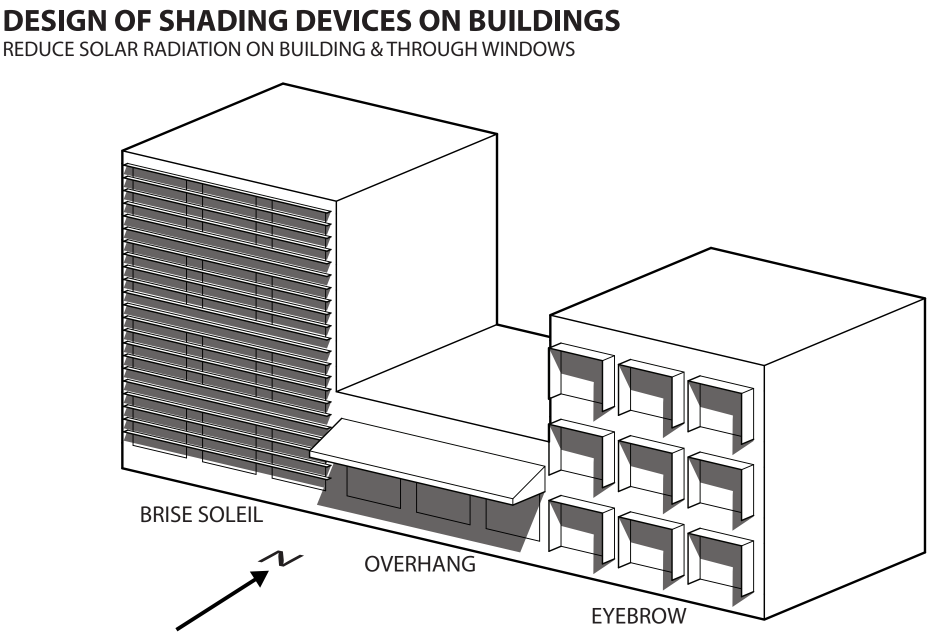

Figure 6.14 **Basic types of fixed building shading devices used to reduce the solar gains through windows and solar irradiation on building surfaces.**

Table 6.15 **Common shading devices evaluated, shown in Figure 6.16.**

Vertical shading	*Vertical twist*
Horizontal shades	Horizontal overhang
	Brise soleil
Egg-crate	Diagonal lattice
	Panel eyebrow
	Cone panel
Perforated skin	Circle packing
	Checkerboard

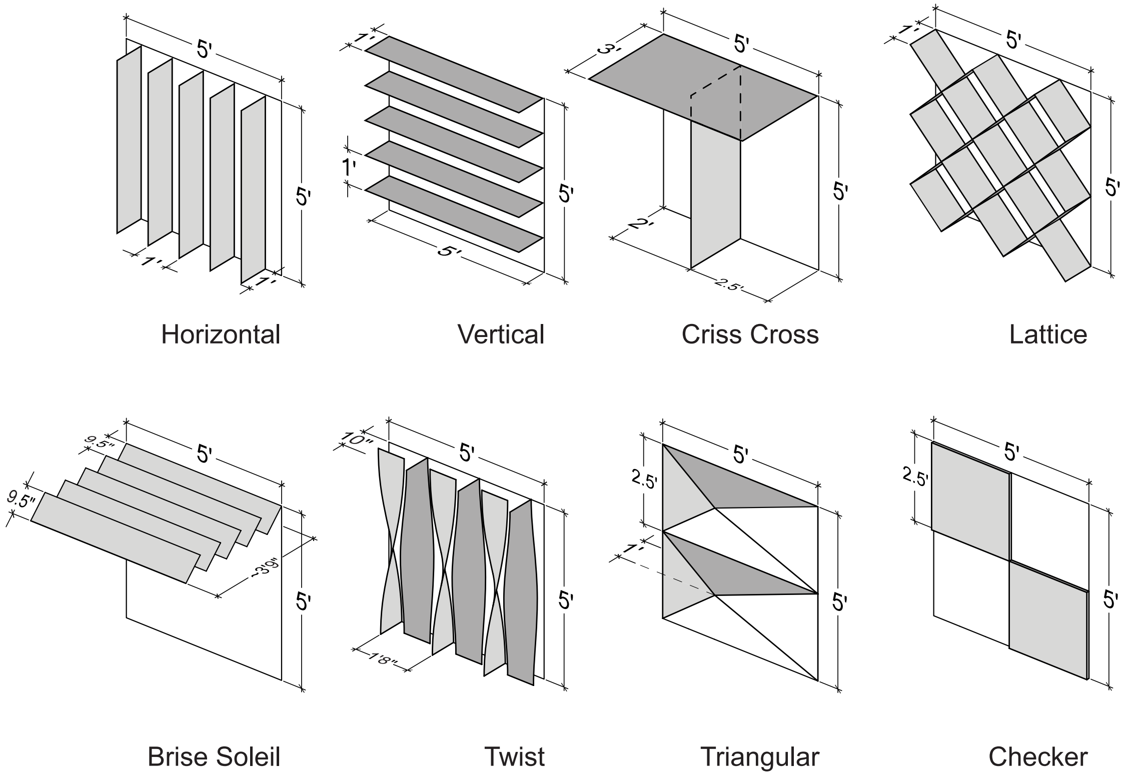

Figure 6.16 **Variety of fixed shading devices evaluated with BEM in the design examples.**

only reduces the annual energy consumption by one percent. Therefore, for the large office building in Miami, designing fenestration to include a brise soleil on the exterior would be worth further evaluation.

Materiality of the Building Envelope

Materials are another important consideration within the BEM. Material choices we make during design do not often affect the building's overall form or design. One of the most common material properties modified to affect the building's performance is a material's thermal conductance, commonly known as its U-factor. Thermal conductance refers to a material's ability to conduct energy in the form of heat. Radiation from the sun heats the material, causing atoms within the material to bump up against each other, and the energy conducts through the material. It follows then that the higher the material's thermal conductivity, the faster heat will pass through it, whereas the lower the thermal conductivity, the longer the heat will take. The material's U-factor ranges from low to high, where the lower the number, the better that material resists thermal conduction, and the higher the number, the less resistance a material has.

Metrics such as surface reflectance also represent in abstract terms how much heat a material absorbs; therefore, reducing the amount of a building's surface area that absorbs heat—say, through large overhangs and other self-shading techniques—will reduce the building's cooling loads in hotter climates. The goal in colder climates, then, is to reduce heating loads during winter by increasing the amount of a material that absorbs the sun's energy. Using these formal strategies along with each material's distinctive properties will help to make the building more energy efficient.

Thermal mass typically refers to a material's ability to absorb solar radiation and store it for later use. It can also help dampen temperature swings, keeping temperatures within acceptable limits. Commonly used in direct-gain systems with direct exposure to the sun, the amount of thermal mass varies depending on the material's location in the building, the needs of the occupants, and the material used.

Design Examples

During design, the formal aspects of a building are constantly evolving and in flux. Energy performance correlates to these changes, and to make informed design decisions about the building's geometry requires awareness of energy performance's interdependence. BEM tools are capable of reporting results quicker and in real time, allowing you to witness the direct impact of geometric variations on energy use. However, informed decision making requires some upfront caveats. Several aspects of the BEM should remain constant from the outset, including climate, material compositions and thermal values, lighting, occupancy, and HVAC settings, none of which should change during geometric design tests. Given these constants, to understand your BEM necessitates discussing two important design aspects: size and windows.

Size Matters

With a simple-box model, playing with the building size will change the energy-use results. A bigger building equals more annual energy use, but sometimes lower EUI. For effective results, you should keep the total building square footage nearly constant during design, since some BEM calculations such as LPD or plug loads are based on square footage. While changing a building's size to save energy is not common, increasing the building volume, on the other hand, may be beneficial.

A larger volume of space with the same square footage may be ideal for daylighting and natural ventilation but, depending on the BEM tool, the energy-use results may or may not reflect this. With a fixed building size, testing formal and volumetric changes within design is possible with BEM. Remember that size matters and more volume will also result in more space to heat and cool.

Windows

Another useful consideration is whether to complete your design exercise with or without windows. It would be valuable to decide this before you start, since it is much harder to understand the design outcomes without a clear expectation of the amount of glazing on a building. As with building size, the results of the BEM simulations hinge upon the amount of glazing. Since glass typically has the highest U-factor or poorest thermal performance, having more of it will dramatically change the gains and losses within the building envelope. If you choose to complete your early analysis without windows, the geometric design solution that achieves the energy-use goals may not be the optimal one once glazing is included. In certain instances, this may be acceptable. Searching for the lowest energy use of a large building mass on a complex urban site or several self-shading building masses or large building forms may be more effectively evaluated without glazing.

Delegating types of glazing to certain parts of a building could be helpful in testing formal design aspects with WWR; for instance, top lighting or clerestories may be one strategy identified for the building. Building these into the early energy model may help define where in the building they might be best located. Another design element may be an all-glass atrium or entry wall. Placing this key feature correctly may be important in deciding the most energy-efficient and best design solution for a particular building site.

Building upon these two caveats, what follows are three basic design examples of how to combine different geometric aspects to evaluate a building during the design process. There are many more methods and a much larger list of building elements to evaluate related to those items outlined above. In the next chapter, we highlight a solution space for office building geometry, though for now, we describe the basic concepts that informed the subsequent analysis in Chapter 7. First, we begin with a common exercise: the conceptual massing study of building forms. Next, we discuss strategies for self-shading building arrangements and their results, and we finish with energy and daylighting issues related to shading devices.

Conceptual Massing

Investigating the energy performance for a range of stacking and aspect ratios is at times necessary to optimize the daylighting and energy performance in a climate. This helps us to determine how, for example, a range of a typical medium-sized office buildings perform, and which building form might perform best for the particular climate. A BEM simulated the building forms (shown in Figure 6.4) of a medium-sized office to evaluate performance across six different U.S. climate zones. The resulting heating and cooling loads are shown in Figure 6.17. The range of performance in each climate is bounded by a dashed line, with each dot on the colored lines representing a different building form and the circles around the

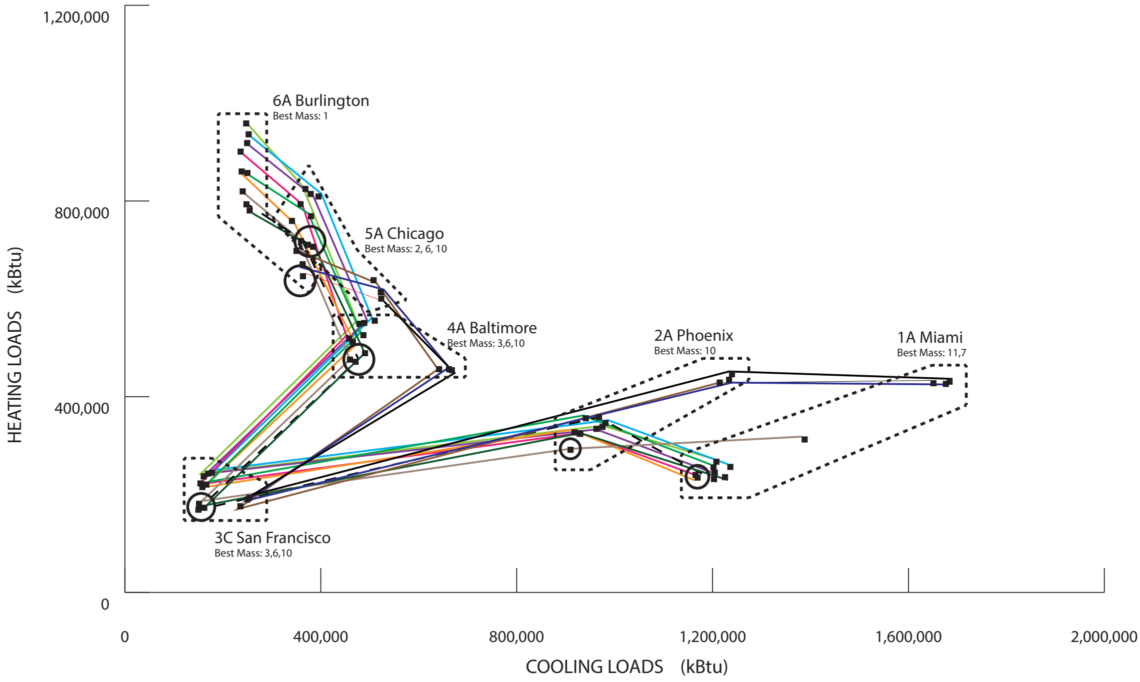

Figure 6.17 **Chart of heating over cooling loads for 12 different buildings across six climates.**

clusters representing the better-performing options. Overall, there are 12 points for six climates, comparing 72 different simulations.

What one can observe in the graph is the behavior of each building form's geometric properties across and within the climate zones. One way to describe the spread of results is to say that those with more variation (in Miami, for instance) have a higher sensitivity, whereas those with a smaller variation (e.g., those in San Francisco) have a lower sensitivity. Within those climates with higher sensitivity and a greater spread of results, it is easy to eliminate the poorly performing options, narrowing the range to those with better results. A city like San Francisco, on the other hand, has a lower sensitivity and a smaller difference between the heating and cooling results for different building forms. Simply viewing their energy performance alone does not provide a clear answer, however, so another metric such as daylighting may be a more useful factor in deciding which building mass may be ideal.

Another observation from the correlation of data, shown in Table 6.18, is that there is no single geometric variable clearly attributed to affecting the performance of this building type across the climates. Within the colder climates (6A and 5A), those masses with more exterior wall (EW/F) or height affect energy performance the most. Within the warmer climates (2B and 1A), however, it is compactness—higher S/V values, lower V/S and F/E values, and more surface area (SOB)—that has the greatest effect on energy performance. However, given another set of criteria in the BEM simulations or site conditions, these results might also vary.

Table 6.18 **Statistical correlation of geometric indices and climate zones for the buildings in Figure 6.4.**

	6A	*5A*	*4B*	*3C*	*2B*	*1A*
V/S	0.63	0.46	−0.28	0.00	**−0.83**	**−0.92**
F/E	0.31	0.08	−0.54	0.16	**−0.84**	**−0.83**
EW/F	**0.78**	**0.81**	0.13	−0.14	−0.51	−0.68
S/V	−0.59	−0.42	0.39	−0.09	**0.91**	**0.96**
Ss/V	0.62	0.67	−0.02	−0.05	−0.52	−0.60
Rc	0.67	0.52	−0.25	−0.01	**−0.84**	**−0.94**
Ratio	−0.02	0.05	−0.20	0.13	−0.09	0.08
Height	**0.91**	**0.90**	0.26	−0.21	−0.50	−0.73
SOB	−0.59	−0.42	0.39	**0.91**	**0.96**	**0.96**
Volume	−0.08	0.10	0.70	−0.25	0.80	0.72

Self-Shading Mass

Another design concept for reducing energy consumption in hotter climates or for internally loaded buildings would be to shade the building. A design concept known as a self-shading building form, the building's specific geometry creates shadows on other parts, thereby reducing solar exposure by casting those building elements in shadow.

By using the aggregation of masses to achieve this effect, the design approach creates a self-shaded building form. One way of doing this is by stacking floor plates on top of one another to achieve the total building square footage. As the various plates overhang and overlap, they shade other plates, thus reducing the building's overall EUI. The concept is relatively simple in that it minimizes the amount of the building's surface area exposed to the sun at any given time over the course of the year or day simulated. The example shown in Figure 6.19 was submitted as part of an international design competition, and yielded an pEUI of 22, the lowest of any in the competition. Part of the iterative design process involved scripting the program and compositional approach in Grasshopper with the goal of reaching the minimal EUI while maintaining the total square footage. By maintaining the building's material, operational, and mechanical system as constant, this script was able to produce the lowest EUI mass of any other design approach. Early experiments of the self-shading script are shown in Figure 6.20.

The core ideas within the self-shading of a building form have a history developed by Ralph Knowles's academic work in the 1960s and 1970s. His studies on the geometric aggregation of spaces in the Native American community of Acoma Pueblo informed ideas involving structures that respond to the sun. His students manipulated different types of geometry based on seasonal exposure to the sun to create complex building forms and shapes. In Figure 6.21, the upturned surface on the left side faces south, with the other side facing east, and the geometry of the façade responds to solar insolation and orientation.

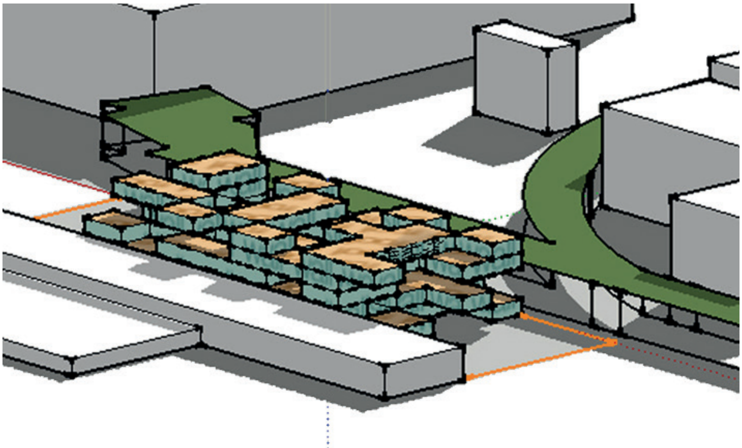

Figure 6.19 BEM example of a self-shaded building by co-author Kaveh Bandhosseini.

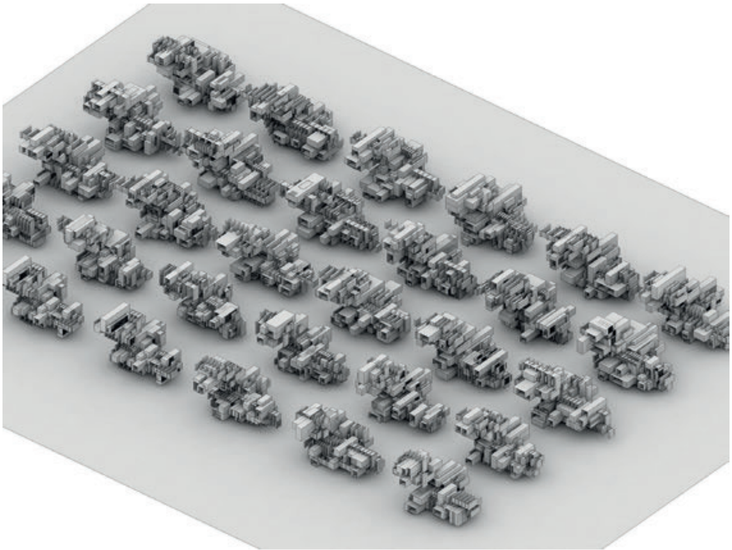

Figure 6.20 A range of scripted autonomously generated shading forms by co-author Kaveh Bandhosseini.

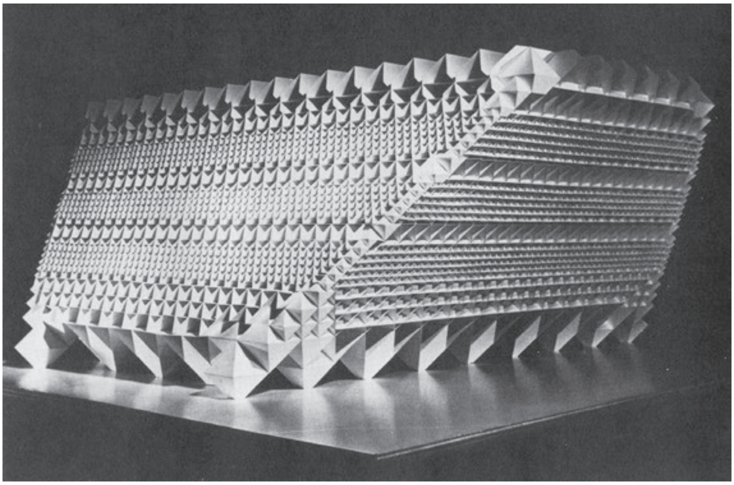

Figure 6.21 Ralph Knowles, *Energy and Form: An Ecological Approach to Urban Growth*, Figure 7.14, page 146, © 1975 Massachusetts Institute of Technology, used with permission of the MIT Press.

Architects in the 1985 text *Design of Energy-Responsive Commercial Buildings* continued to explore Knowles's ideas. A case study of William Morgan Architects' Federal Building in Ft. Lauderdale, Florida demonstrates self-shading in the formal response of the building form that shades the glass. All windows are located under broad overhangs or within notches carved from the building's corners, and the exposed perimeter walls are solid and opaque.[16]

Daylight and Energy Optimization

Within fenestration, designers attempt to combine the material characteristics of the glazing, WWR, and shading device design. To illustrate this process, we follow with a BEM example of how the shading devices identified above affect interior daylighting and overall energy use (in most BEM tools, daylighting is a separate entity that doesn't factor directly into energy consumption).

The sample we evaluate uses a 45-foot cube, a three-story office building placed within six climate zones. We vary the shading devices, as shown in Figure 6.16, on each side of this all-glass volume. At the outset we had an EUI of 91, with the daylighting metrics showing 100 percent sDA (great!) but also 100 percent ASE (bad). The goal was to maintain a high sDA value while minimizing ASE, simultaneously reducing energy consumption. Throughout the exercise, all other factors remained constant. Testing the different shading devices across a range of climates produced a best result of an ASE of 74 and an EUI of 77. While not dramatic, this process does demonstrate the effects shading devices have on reducing unwanted glare and conserving energy.

Iterative testing of the shading devices used an instance of a shading device system from the design software reloaded into energy modeling software (Figure 6.23). This process allowed quick feedback to test different design considerations. Since the energy and daylighting metrics respond alongside the design decisions, we were able to reach easy and quick conclusions. There are ways to

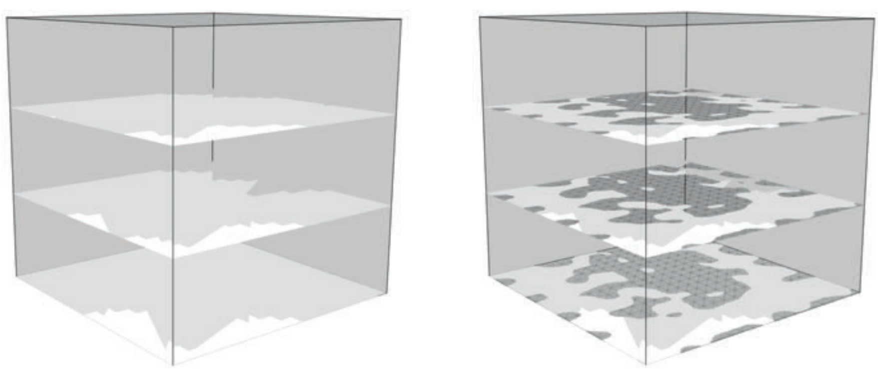

Figure 6.22 **Visual comparison of the all-glass baseline sDA (left) against the best sDA result from shading devices (right).**

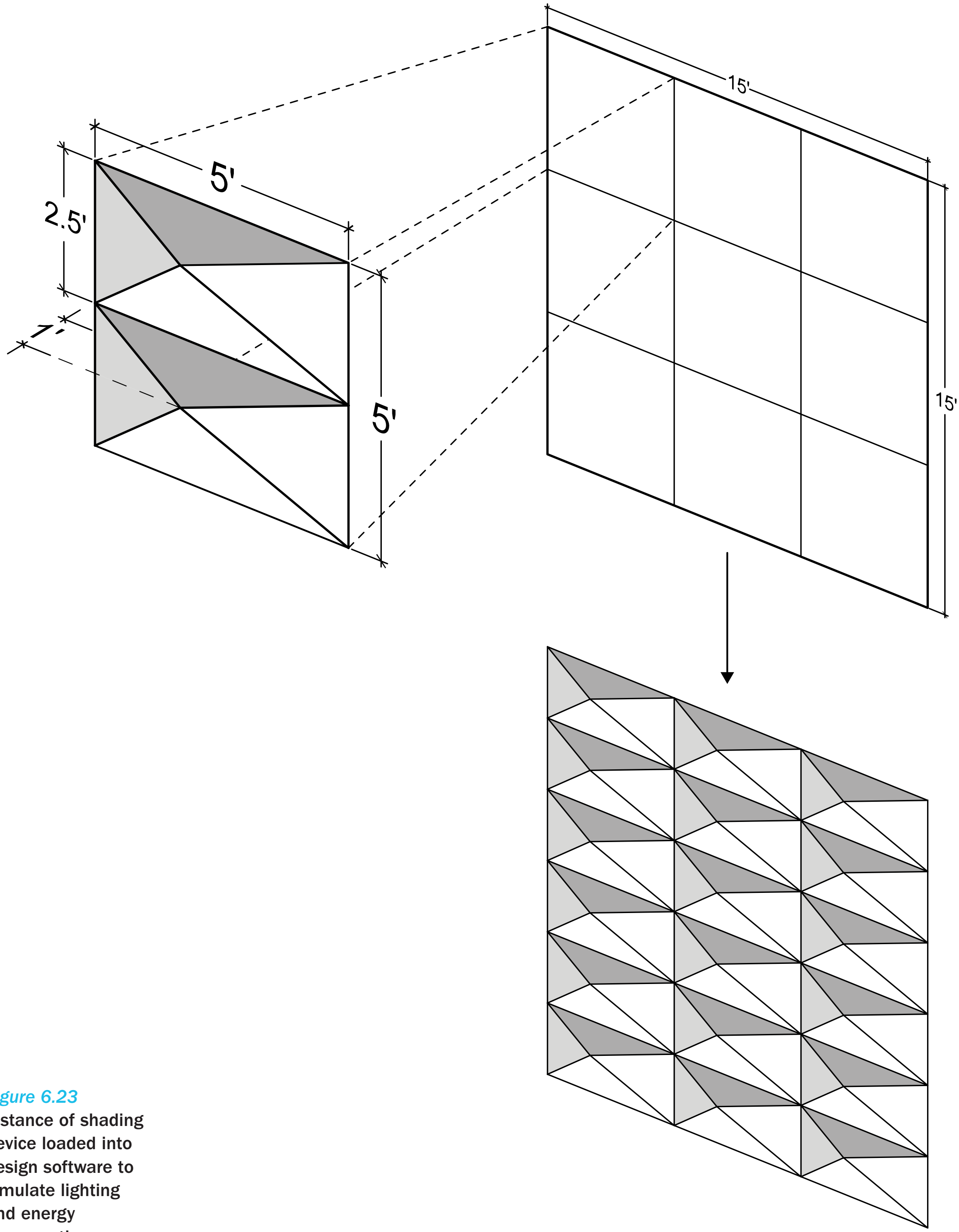

Figure 6.23
Instance of shading device loaded into design software to simulate lighting and energy consumption.

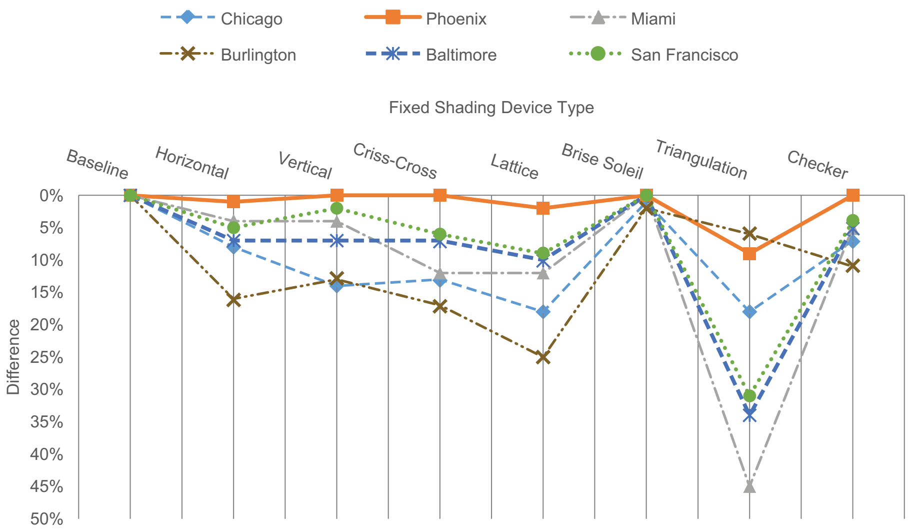

Figure 6.24
Chart showing the percentage difference between sDA and ASE values for seven fixed shading devices across six U.S. locations.

further this exploration through variations in the depth and spacing of the shading devices to achieve an optimal minimum ASE or EUI.

Across all the examples, the sDA remained at 100 percent; Figure 6.24 shows the difference between the ASE and sDA values. Based on the results, almost all of the shading devices have some impact on reducing ASE, but the triangular shading device reduced glare the most. Since our baseline building is all glass, the next design step could evaluate the daylighting metrics alongside a reduction in the glazing amount to see how much more we can reduce the ASE and EUI values.

Designing for Energy Performance

Evaluating single building aspects and discrete elements provides designers, architects, and engineers with the ability to weigh each element's sensitivity and range of energy performance. For instance, being able to understand and demonstrate that a building's orientation has little impact on energy use might offer other opportunities to consider in design. Or, if orientation is a significant factor because of daylighting potential to reduce internal gains from lighting, using BEM early can help the project team prioritize this goal and better understand the steps to achieving it. The design examples of different building forms, self-shading masses, and sun-shading devices demonstrate how BEM aids in making early design decisions to reduce energy use.

Using the BEM design framework from this point forward, one can design to maximize architecture's effect on energy conservation. This is important in identifying where you can make the biggest impact on energy use. However, as discussed briefly, not all of these items act individually on a building's energy use—many have global, whole-building impacts, and require complex simulations to understand.

Exercise: Test a Range of Building Forms

To evaluate a range of building forms or geometry, create a series of different aspect ratios and stacking ratios. Combine the outcomes of these two and generate a series of forms to evaluate with BEM.

Fixed variables

- Climate zone;
- building type;
- square footage;
- total floor-to-floor height.

Design-dependent variables

- Aspect ratio (AR);
- stacking ratio (SR).

Resulting combinations to model and evaluate using BEM

- AR1:SR1; AR1:SR2; AR1: SR3;
- AR2:SR1; AR2:SR2; AR2: SR3;
- AR3:SR1; AR3:SR2; AR3: SR3.

Notes

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9 Rodrigues, "Geometry-based Building Indices," 562.
10 Ibid., 571.
11 Ibid.
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7 Issues with BEM

Introduction

The typical opening for literature dealing with performance issues in architecture would highlight the importance of statistical data in order to save energy in the building sector while emphasizing that there is room for improvement. Such approaches usually continue by delving into the opportunities opened up by new simulation technologies and mention the hardships and costs of the technical management of informing design decisions with performance data.

All of these issues are very real and true, yet there is another aspect omitted: the design appeal of the approach itself. To provide some context, it is possible to refer to the widely accepted rule that energy modeling in the early stages is more effective than energy modeling in the later stages. This rule leads to the simple-box modeling approach that can be helpful for architects—so helpful, in fact, that the current research easily falls within the same boundary. But at the same time, the simple-box approach is simplistic in the sense that the simple-box itself can be engulfed in the sea of decisions that comprise a building's design. It may also be unfair to call such design performance-based, as the degree to which performance plays a role may not be that great. As a result, the risk is reducing performance-based design to a parametric shading or a simple simulation that is not nearly as exciting as the other available alternatives in the digital age.

Designing based on performance, however, can be both very exciting and very complicated. In the theoretical context of avoiding the architect as master creator, making design decisions based on styles or ideological allegiances and in general imposing a subjective will on the material,[1] performance-based design can be used to generate new and even unpredictable forms.

The advent of advanced computation, in other words, means that the conceptual and engineering aspects of architecture can stand in agreement with each other; or performance aspects need no longer be external to the building design and form making. Would the architectural community support pushing

performance-design to its extremes to achieve the optimal form? Maybe because such design includes a loss of control on the part of the architects, or perhaps this process involves a certain level of idealism, but it is also because the phrase *the optimal form* lends itself to varying interpretations. However, if other designers are curious to know or define what these versions of the optimal can be, there are still a few obstacles to overcome.

This chapter locates some of these obstacles to defining the optimal while also suggesting ways around them. In other words, our objective is to achieve a malleable methodology to evaluate and optimize the performance of geometries in a holistic framework.

WBEM Obstacles

A relatively new user might hear about the whole-building energy model (WBEM) and be excited about the ease with which a certain software package can execute such analysis. As logical as that expectation might be in the digital age, however, in reality (at least up to now), no software actually offers such a whole-building analysis, and there is not even a clear-cut methodology for such a process! One reason is that many buildings are too complex to simulate as a whole; thus, the whole is broken into pieces, each simulated separately and then pieced back together within the reporting results. Here, on the one hand, neglecting certain aspects of energy consumption may occur in the process, creating an effect on the overall resultant performance-based form. On the other hand, within a WBEM methodology—usually called one parameter at a time optimization—a certain linearity replaces the actual complexity of the system.

To state it more clearly, at times no parameter has primacy over the others, and choosing one particular parameter by which to start affects the result. In this milieu, the most relevant example is probably lighting. By giving a certain primacy to thermal optimization, as is the case with current WBEM, the modeling process postpones the lighting calculation, effectively omitting it from consideration. A real WBEM optimization, however, should synchronize the involved factors and account for the actual complexity of the system—at least to the extent that it is possible.

Lighting

The omission within most WBEM frameworks is the dynamic and differential effect of the sun and solar gains, flattening lighting power density (LPD) into a single number. LPD considers only the building function and the total area, and does not reflect on the building geometry, the window shape and size, or numerous other relevant aspects of the building. For lighting energy use, LPD is the default

calculation in most software packages; because LPD allows quick calculations it is possible to produce numerous results and iterations (Figure 7.1). Since the floor areas and building volumes are equal across the range, so too is the resulting lighting electricity consumed.

By ignoring the daylight that penetrates through the windows, the WBEM calculation is primarily thermal-based. While this might have its own applications, it represents and emphasizes only one set of forces, which drives the geometry toward a more compact and less transparent shape. The logical result, as Figure 7.1 shows, may end up being a square plan with the lowest WWR (window-to-wall ratio).

The geometry discovered from thermal influences protects the core of the building and results in relatively poor lighting. In reality, however, daylighting forces drive geometries toward a narrower and more transparent result. The narrowness may occur in the plan or in the section (such as in towers with multiple floors in comparison to a bulk single-floor plan with the same area), but in general the floors are pushed closer to the windows and a larger part of them is exposed to daylight. As one can see, thermal and lighting forces are opposed, and this presents designers with exciting opportunities to experiment with different formal strategies for locating the sweet spot where the building's thermal and lighting needs optimally balance each other.

Thus, one can expect within a WBEM a unifying framework in which the energy consumed by electric lighting and the energy needed for thermal purposes can merge into a whole unit. As mentioned earlier, the main obstacle here is that research on lighting—while advancing quickly and introducing a new wave of dynamic metrics—moves separately from the other building metrics, meaning that there is therefore no unanimously accepted methodology for a whole-building energy analysis. Before proposing a solution, we should briefly examine some different aspects of this problem:

- Lighting research introduces dynamic metrics (such as spatial daylight autonomy (sDA) and annual sunlight exposure (ASE)) that do not directly address energy consumption. The latest manual (IES LM-83-2012), for example, avoids the problem, saying only that "electric lighting management is highly variable."[2]
- Transforming the lighting metrics into energy units includes esoteric assumptions and decisions that may not be convenient (or at least might not be the main concern) for architects involved in the early stages of design.
- Lighting calculations are complicated and much slower than thermal ones. Hence, when synchronizing the two, one should expect a lower resolution in any BFM or evolutionary algorithm. Cloud-computation technologies may be helpful in this regard, but uploading and downloading iterative data and working within networking frameworks has its own challenges.

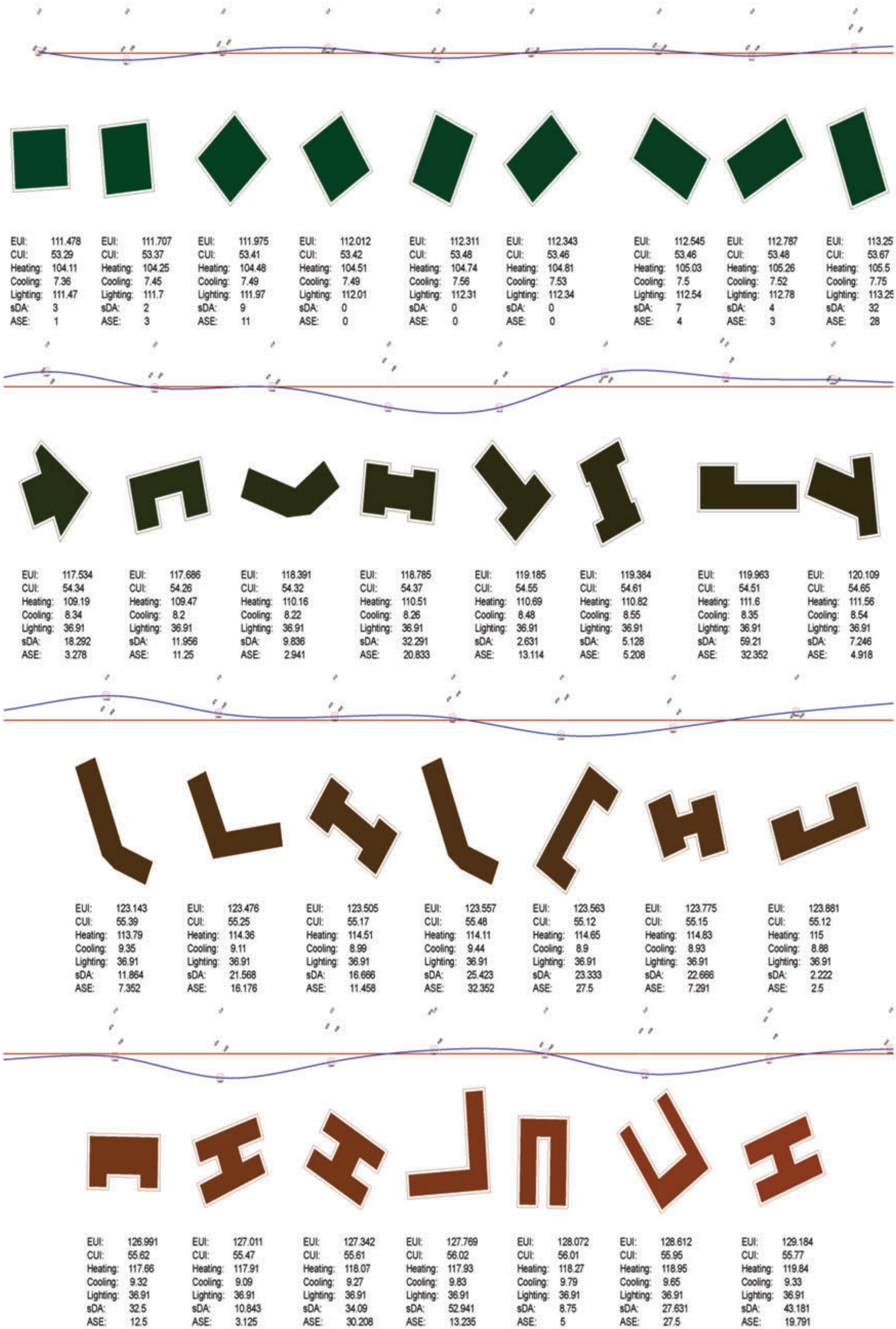
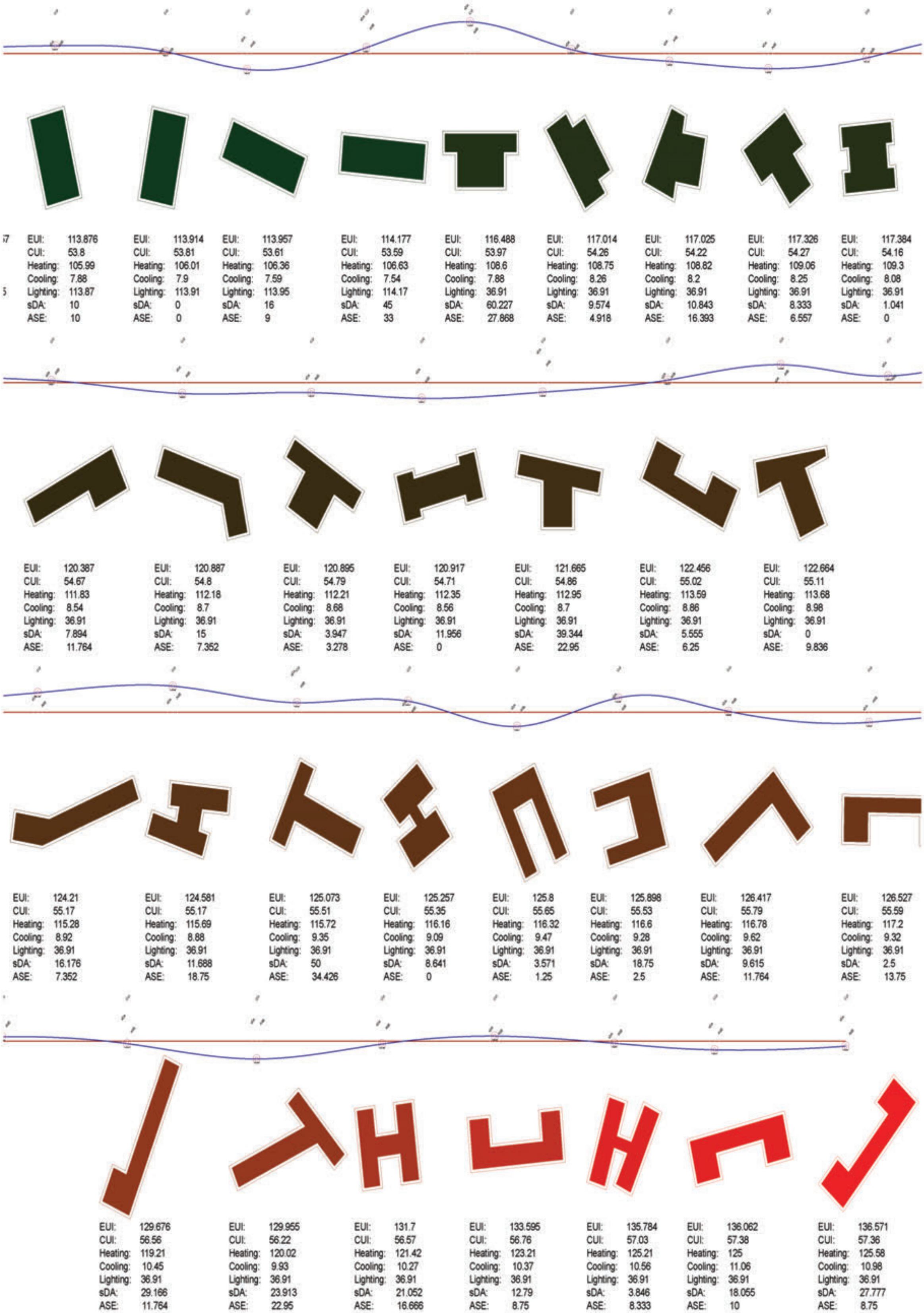


Figure 7.1 **Whole-building energy analysis using LPD for the lighting energy consumption**



EUI: 113.876 CUI: 53.8 Heating: 105.99 Cooling: 7.88 Lighting: 113.87 sDA: 10 ASE: 10
EUI: 113.914 CUI: 53.81 Heating: 106.01 Cooling: 7.9 Lighting: 113.91 sDA: 0 ASE: 0
EUI: 113.957 CUI: 53.61 Heating: 106.36 Cooling: 7.59 Lighting: 113.95 sDA: 16 ASE: 9
EUI: 114.177 CUI: 53.59 Heating: 106.63 Cooling: 7.54 Lighting: 114.17 sDA: 45 ASE: 33
EUI: 116.488 CUI: 53.97 Heating: 108.6 Cooling: 7.88 Lighting: 36.91 sDA: 60.227 ASE: 27.868
EUI: 117.014 CUI: 54.26 Heating: 108.75 Cooling: 8.26 Lighting: 36.91 sDA: 9.574 ASE: 4.918
EUI: 117.025 CUI: 54.22 Heating: 108.82 Cooling: 8.2 Lighting: 36.91 sDA: 10.843 ASE: 16.393
EUI: 117.326 CUI: 54.27 Heating: 109.06 Cooling: 8.25 Lighting: 36.91 sDA: 8.333 ASE: 6.557
EUI: 117.384 CUI: 54.16 Heating: 109.3 Cooling: 8.08 Lighting: 36.91 sDA: 1.041 ASE: 0
EUI: 120.387 CUI: 54.67 Heating: 111.83 Cooling: 8.54 Lighting: 36.91 sDA: 7.894 ASE: 11.764
EUI: 120.887 CUI: 54.8 Heating: 112.18 Cooling: 8.7 Lighting: 36.91 sDA: 15 ASE: 7.352
EUI: 120.895 CUI: 54.79 Heating: 112.21 Cooling: 8.68 Lighting: 36.91 sDA: 3.947 ASE: 3.278
EUI: 120.917 CUI: 54.71 Heating: 112.35 Cooling: 8.56 Lighting: 36.91 sDA: 11.956 ASE: 0
EUI: 121.665 CUI: 54.86 Heating: 112.95 Cooling: 8.7 Lighting: 36.91 sDA: 39.344 ASE: 22.95
EUI: 122.456 CUI: 55.02 Heating: 113.59 Cooling: 8.86 Lighting: 36.91 sDA: 5.555 ASE: 6.25
EUI: 122.664 CUI: 55.11 Heating: 113.68 Cooling: 8.98 Lighting: 36.91 sDA: 0 ASE: 9.836
EUI: 124.21 CUI: 55.17 Heating: 115.28 Cooling: 8.92 Lighting: 36.91 sDA: 16.176 ASE: 7.352
EUI: 124.581 CUI: 55.17 Heating: 115.69 Cooling: 8.88 Lighting: 36.91 sDA: 11.688 ASE: 18.75
EUI: 125.073 CUI: 55.51 Heating: 115.72 Cooling: 9.35 Lighting: 36.91 sDA: 50 ASE: 34.426
EUI: 125.257 CUI: 55.35 Heating: 116.16 Cooling: 9.09 Lighting: 36.91 sDA: 8.641 ASE: 0
EUI: 125.8 CUI: 55.65 Heating: 116.32 Cooling: 9.47 Lighting: 36.91 sDA: 3.571 ASE: 1.25
EUI: 125.898 CUI: 55.53 Heating: 116.6 Cooling: 9.28 Lighting: 36.91 sDA: 18.75 ASE: 2.5
EUI: 126.417 CUI: 55.79 Heating: 116.78 Cooling: 9.62 Lighting: 36.91 sDA: 9.615 ASE: 11.764
EUI: 126.527 CUI: 55.59 Heating: 117.2 Cooling: 9.32 Lighting: 36.91 sDA: 2.5 ASE: 13.75
EUI: 129.676 CUI: 56.56 Heating: 119.21 Cooling: 10.45 Lighting: 36.91 sDA: 29.166 ASE: 11.764
EUI: 129.955 CUI: 56.22 Heating: 120.02 Cooling: 9.93 Lighting: 36.91 sDA: 23.913 ASE: 22.95
EUI: 131.7 CUI: 56.57 Heating: 121.42 Cooling: 10.27 Lighting: 36.91 sDA: 21.052 ASE: 16.666
EUI: 133.595 CUI: 56.76 Heating: 123.21 Cooling: 10.37 Lighting: 36.91 sDA: 12.79 ASE: 8.75
EUI: 135.784 CUI: 57.03 Heating: 125.21 Cooling: 10.56 Lighting: 36.91 sDA: 3.846 ASE: 8.333
EUI: 136.062 CUI: 57.38 Heating: 125 Cooling: 11.06 Lighting: 36.91 sDA: 18.055 ASE: 10
EUI: 136.571 CUI: 57.36 Heating: 125.58 Cooling: 10.98 Lighting: 36.91 sDA: 27.777 ASE: 8.75

Parallel Example (Literature Review)

As expected, because dynamic lighting metrics are relatively new, the available literature is thin. Designers and computation experts, however, are gradually facing the problem of dynamic lighting metrics more often, and one may expect further developments in the near future. A recent example is the work of Kyle Konis's team, which refers to the problem of synchronizing thermal lighting calculations[3] and recommends using a new metric, spatial useful daylight illuminance (SUDI).[4] To synchronize the results they suggest that the values should be "scaled to the same numerical range (e.g., 0–100)."[5]

While the gap in the existing knowledge (i.e., a method of synchronizing thermal and lighting results) may legitimize radical solutions such as inventing a new metric, this new methodology still leaves the transformation from metrics of daylighting to units of energy undetermined. In other words, remapping and adding the results of thermal calculation (which is an energy metric) and lighting calculation (which is a percentage value) is not accurate, and does not reflect the actual building's performance. This movement from lighting metrics to energy metrics includes more assumptions and decisions that remain undiscussed and unresolved.

Methodology

The main element of the current methodology is to avoid closing the space of discussions or arguing for a single correct answer. Instead, in the following pages several methods and their results are placed next to one another to provide extensive information on this issue. Before getting into the technicalities, defining these main approaches can be helpful:

LPD: As mentioned previously, lighting power density is an ineffective way to ascertain a building's lighting needs. However, the metric will be provided to establish a baseline. Because the total floor area and the building functions remain the same across each group of iterations, the LPD value will remain constant.

Dimming schedule: A conventional way to adjust a building's lighting power consumption is to inform it with a lighting calculation based on climate data (also known as *climate-based* in DIVA). Based on a predefined set point (target illuminance level), photo-sensor-controlled dimming will provide a schedule that defines whether lighting switches are on or off in a given area at a given time over the course of the year. The dimming system itself consumes some energy (referred to as standby power and ballast loss factor) that should be included. Thus, if an area has sufficient illumination, the building's dimming system will reduce energy consumption by turning off the lighting in that area.

Reduced LPD: Compared with the previous option, reduced LPD requires both a prior lighting calculation and the sDA number produced. Using the sDA number to modify the LPD number reflects the possibility of using natural

light. This approach is a practical solution that is fast and useful, and was suggested first by the Sefaira team.[6] Equation 7.1 shows the formula used, which is also simple:

$$\text{Reduced LPD} = [(1 - \text{sDA} / 100) \times 0.8 + 0.2] \times \text{main LPD} \quad (7.1)$$

sDA-based lighting (lux deficiency method): This method is specific to the current research and is suggested by the author, hence, it requires a bit more explanation. It makes use of the basic structure of sDA calculation as depicted in Figure 7.2.

sDA is calculated based on a grid of sensors. At a certain sensor, if the lux level is above the threshold (300 lux is currently the only threshold endorsed by the Illuminating Engineering Society [IES]), there is no need for artificial lighting and the power consumption would be zero. However, if the lux level is below the threshold—say, $x = 250$—the artificial lighting needed should provide *threshold* $- x$, or 300 – 250 lux at that specific point, yielding a result of 50 lux. The sDA calculation also predefines the grid size (or more specifically, its area), and so the only missing bit of information is the lighting type. By determining the lighting source, it is possible to obtain the luminous efficacy (lm/W). Regular numbers in Table 7.3 show luminous efficacy for lighting types, but note that it is possible to use a mixture of different types to achieve different results.

With the available information (i.e., the extra illumination needed [in lux], the area, and the lighting type) it is possible to calculate the needed electrical energy at a certain point on the grid. The power P in watts (W) is equal to the illuminance E_v in lux (lx) times the surface area A in square meters (m_2) divided by the luminous efficacy η in lumens per watt (lm/W),[7] shown in Equation 7.2:

$$P = E_v \times A / \eta \quad (7.2)$$

Of course, the total lighting consumption would be the cumulative sum of the values across all of the sensors in the grid over time. Similar to the

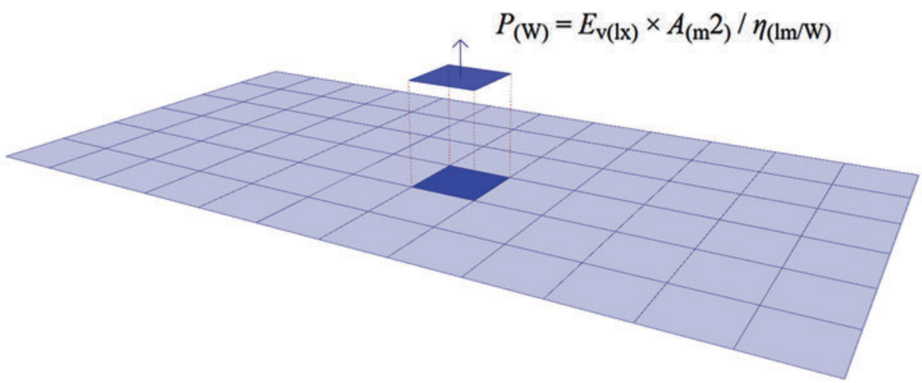


Figure 7.2
Diagram showing how to move from the sDA metric to energy consumption.

Table 7.3 **Luminous efficacy for common lighting sources.**

Lighting type	*Luminous efficacy (lm/W)*
Tungsten incandescent light bulb	15
Halogen lamp	20
Mercury vapor lamp	50
Fluorescent lamp	60
LED lamp	60
Metal halide lamp	87
High pressure sodium vapor lamp	117
Low pressure sodium vapor lamp	150

dimming schedule option, this approach should consider a consumption value for the control and distribution system. In any case, however, the internal consistency achieved across all of the iterations should be sufficient for both evaluating energy performance and defining energy optimization goals.

IES defines sDA as the "asset value of daylight sufficiency";[8] and this method is based on using the lux deficiency to calculate the necessary energy. In returning to the difference between daylight autonomy (DA) and continuous daylight autonomy (CDA), we find a similar situation; sDA cuts the results at 50 percent, meaning that 49 percent and 51 percent suddenly become very different. The lux deficiency method, however, calculates the extra illumination needed for the points that do not meet the requirements, and thus provides a more distributed result similar to CDA. In this method, 49 percent and 12 percent are both failing numbers, but the energy needed to compensate for the lack of illumination is different in each case.

As a final note, and to put these methods in their contexts more properly, it is worth mentioning that the first two, namely LPD and the dimming schedule, were used even before the dynamic metrics (such as sDA) were available, which is probably why they are still widely used. LPD is in fact independent from any actual lighting calculation and the dimming schedule method can be produced by traditional types of climate based analysis—for example the conventional DA (daylight autonomy). The new dynamic metrics, however, may require new methods for the calculations as well. Reduced LPD and Lux deficiency methods are, accordingly, the attempts at embedding the lighting calculation within the processes and loops of the sDA procedure, both for consistency and for saving time.

Preparation

In general, the current research is an attempt to align as closely as possible with sDA/ASE, and many of its aspects are accordingly defined by those metrics. For example, the goal of the process discussed in this chapter was to engage with a wide range of possibilities, including different climates, geometries, types, and

sizes. It would then make sense to use different types of workspaces with different illuminance thresholds, especially in spaces with decidedly disparate visual tasks or illuminance needs such as warehouses, office spaces, or healthcare facilities. But IES LM-83-12 "does not have a research basis for recommendations for such areas"[9] yet, and as such, using different illuminance thresholds with such disparate workspaces would be viewed as coming far too soon. Therefore, under the title of *office space*, only a single building type with a threshold of 300 lux is studied. Some of the variables, however, include:

Building size: Three different office size categories are analyzed in Table 7.4, essentially using the prototypes by the U.S. Department of Energy.

Climate: Choosing several climates in the U.S., the simulations used four cities (New York, New York; Omaha, Nebraska; Phoenix, Arizona; and Miami, Florida) to represent four different conditions and determine how climate affects the results.

Geometry: A letter-shape strategy was used in which shapes were categorized into different groups: L, T, O, H, U, and trapezoidal. Such forms are functional, but are at the same time not overly simplistic, establishing a middle ground between pure simple-box modeling and complex agent-based formal strategies. Windows distribution was equal over all sides (walls). If the total square footage of the building is lower than 25,000 ft^2 (2,322.576 m^2), a WWR of 25 is used. For larger buildings, the WWR would be 30. It might make sense to have a larger window on the south or north side; the aim here is not to optimize the form but rather to show the performance behavior of changing forms. Across each of the iteration groups (small, medium, and large) created here, the total square footage and volume remain constant so that the geometries continue to be comparable. The floor to floor height also changes as we move toward larger offices, from 3 m for the small and medium shapes to 5 m, therefore studying each group separately (i.e., small offices against small offices, and not against large or medium offices) makes more rational sense.

Materials and conditions: Better material generally leads to better performance. Accordingly, in this study, materials remain unchanged in the hope that the focus will shift toward geometry and design. Keeping the two completely separate is not possible, because as surfaces such as roofs or walls change in different iterations, the material composition of the building changes as well. That being said, the items listed in Table 7.5 remain consistent across all of the iterations in this study.

When synchronizing thermal and lighting simulations, another issue, material consistency, is of high significance. Material consistency is more important

Table 7.4 **Typical office sizes evaluated in simulations.**

Office size	*Area (ft^2)*	*Area (m^2)*	*Floor to floor height (m)*	*Number of floors*
Small	5,000	464.5	3	1
Medium	50,000	4,645.1	4	1–3
Large	500,000	46,451.5	5	1–12

Table 7.5 **Constant items for simulations.**

Material/condition	*Value*
Walls	R = 30
Floor	R = 20
Roof	R = 80
Window	U = 1.32 W/m^2K
Heating set point	21.66 °C (71 °F)
Cooling set point	24.44 °C (76 °F)

Table 7.6 **Material consistency for thermal and lighting calculations.**

Material	*SHGC*	*U-factor (W/m^2K)*	*Visual transmission %*	*Visual transmissivity (RGB) %*
Glazing SinglePane 88	0.82	5.82	88	96
Glazing DoublePane Clear_80	0.72	2.71	80	87
Glazing DoublePane LowE 65	0.28	1.63	60	71
Glazing DoublePane LowE Argon 65	0.27	1.32	65	71

when dealing with transparent items, i.e., windows. If selecting a specific window for the building, one should use both the thermal and lighting properties from that same window's materiality. This process might not be—and usually is not—automated, and requires some extra attention. Table 7.6 lists examples of different properties that come with common window types.[10]

Analysis period: Similar to the problem of building type—which is limited to only one—here again there are limitations imposed by IES LM-83-12. According to the manual, "the period of analysis is fixed at 10 hours per day, from 8AM to 6PM local time," which "results in 3,650 hours for a complete annual analysis."[11] While this limitation excludes schools or other buildings with varying schedules, for now, the insistence on unifying buildings with such disparate schedules forms a necessity "for specification and reporting so that comparisons can also be made to a consistent performance standard."[12]

Analysis grid: Admittedly, and as Figure 7.7 shows, changing only the grid size while keeping all other factors constant does indeed affect the result. Thus, to report a consistent performance standard, one should use the grid suggested by IES LM-83-12. However, that grid (24") requires too many sensors, especially for the large offices (500,000 ft^2). Because of the limitations in calculation power, the grid sizes shown in Table 7.8 were used. Other aspects of the grid based on IES LM-83-12 are a threshold of 300 lux (27 foot-candles) and a height of 0.8 m.

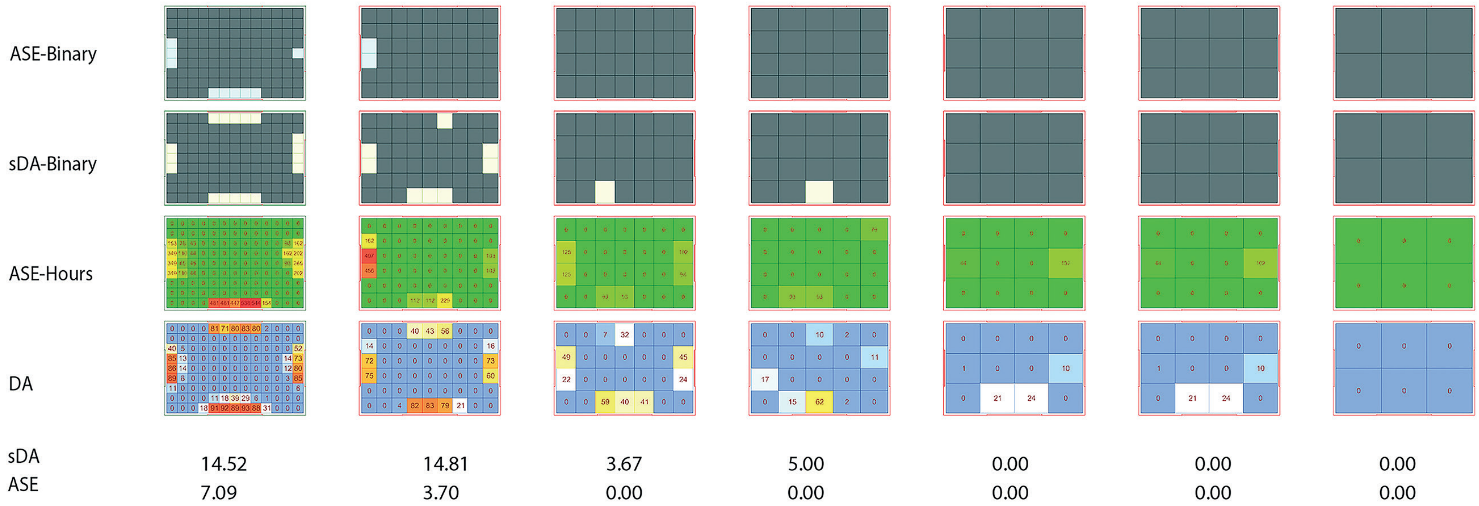


Figure 7.7 The effect of grid size on analysis results.

Table 7.8 **Grid sizes.**

Building size	***Grid***
Small	3 ft (0.9 m)
Medium	4 ft (1.2 m)
Large	8 ft (2.4 m)

Software Details

The entire study was conducted inside Rhinoceros (a NURBS modeling tool). Geometries are exported as meshes to Grasshopper (GH). To perform the iterative study, GH and a Python script were used, though the most important package was DIVA v3 for GH, which provided the links to EnergyPlus and Daysim for thermal and lighting calculations, respectively.

Furthermore, sDA works paired with ASE. For that reason, two separate daylight analyses are performed, one with six bounces and the other with zero. The six-bounce version has a threshold of 300 lux, and the zero-bounce version has a threshold of 1,000. The only benefit of calculating the sDA number by computational programming is that calculating lux deficiency and sDA can occur within the same loop, saving a bit of calculation time. In other words, if illuminance at a certain sensor is above 300, it qualifies to be added to the temporal dimension of sDA. Later, one should test whether this is above or below 50 percent of the schedule, and if not, it is possible to calculate and accumulate $300 - x$, which gradually builds up the total deficiency.

The thermal component is a simplified single-zone analysis in which the whole building is one zone—internal floors used for lighting calculations are nonexistent in the thermal calculations. The modified LPD value, or the dimming schedule, is then passed to the thermal component to complete the analysis. For the lux deficiency method, LPD = 0 is used, and the result of the light calculation (electricity, as expressed in kWh) generates the source energy and the carbon emissions.[13]

Visualization of Results

While it is possible to use genetic algorithms to optimize the form based on predefined goals, using a strategy closer to brute force in this study helped to organize the results based on the total energy consumption. This is because in packaged genetic algorithms, the process remains undisclosed and only the results are visible; however, with BFM it is possible to observe how factors such as ratio, orientation, and the others evaluated affect the behavior of forms in relation to energy consumption.

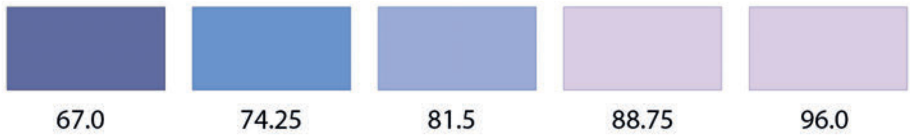


Figure 7.9
sDA color-coding example.

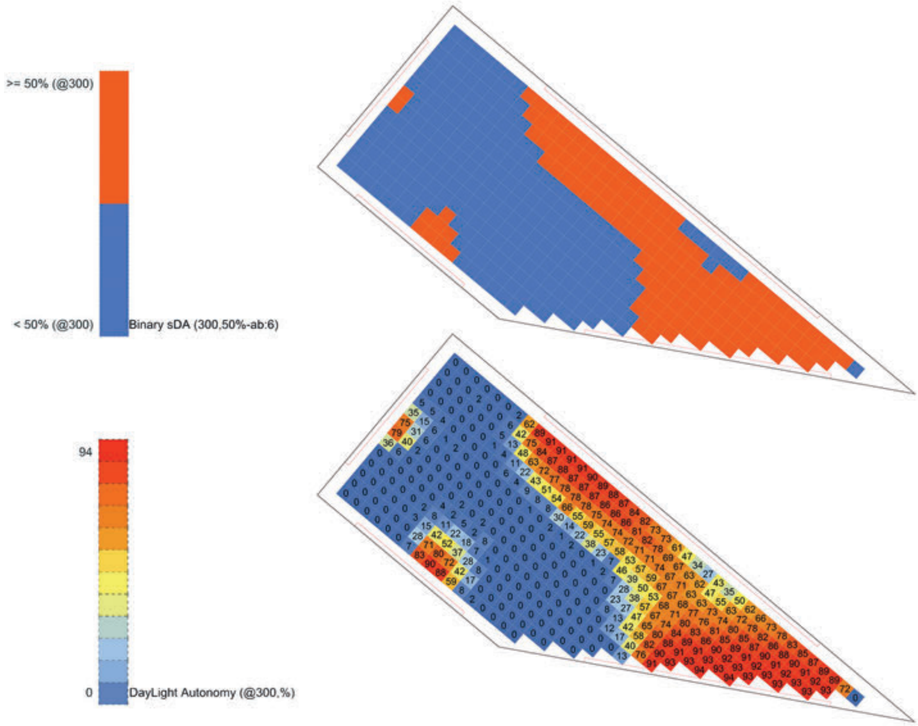


Figure 7.10
Binary sDA.

Using a particular visual style helps to provide clear information. For example, as Figure 7.9 shows, sDA itself is just a number that may work in comparison with other buildings and their sDA values, but it does not disclose much information about the building. For this reason, in the current study the results report a visual style called binary sDA. Figure 7.10 shows an example of binary sDA.

The process in Figure 7.10 is simple; the lower figure shows a sDA with the threshold of 300 lux and the upper figure shows whether or not that value is above 50 percent. At the same time, based on the brighter part of Figure 7.10, the sDA value is visualized.

The other style is binary ASE, depicted in Figure 7.11. Here, the lower image demonstrates the number of hours that a certain area is exposed to direct sunlight, and the upper image shows whether or not the time of exposure to direct sunlight is above 1,000 hours per year. Again, in this picture one can also observe the ASE value. Finally, as Figure 7.12 shows, graphing key metrics of the

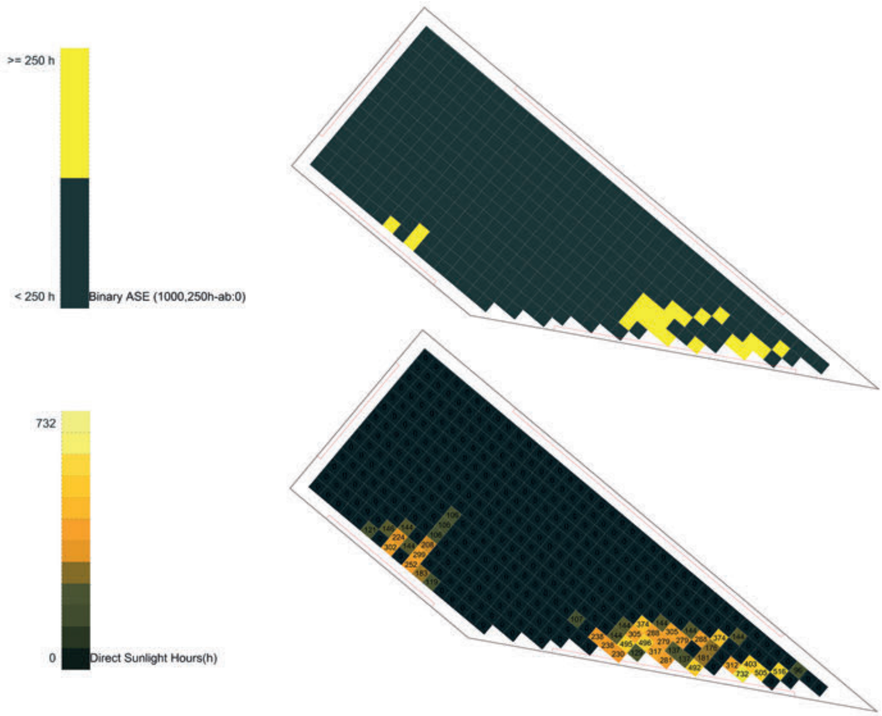


Figure 7.11
Binary ASE.

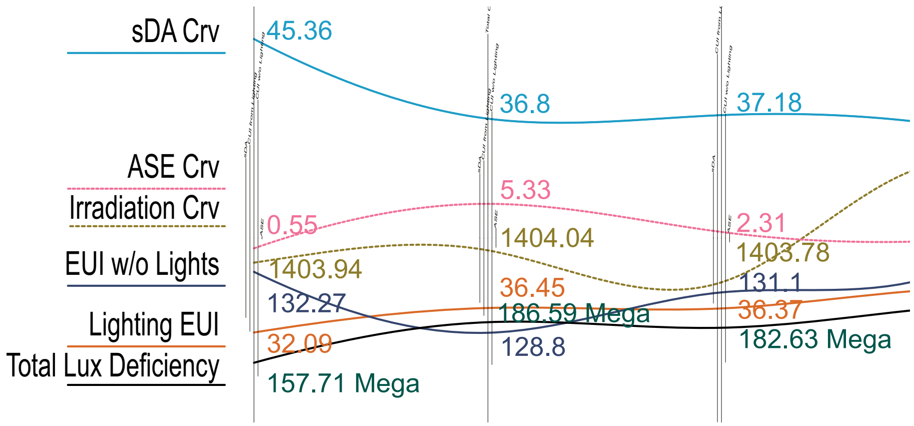


Figure 7.12
Line graphs showing the behaviors of each iteration of the building simulation.

buildings compare each result to provide additional insight into the behaviors of the forms.

Pattern Guide

In this truer WBEM study, the following pattern guide (Figures 7.15–7.38) demonstrates the results of the research integrating lighting energy into the WBEM

geometric building variations. Each building is modeled and simulated in isolation; therefore, no shading from context is included and the number of iterations depicted are limited because they are bound to the print size. Nevertheless, our hope is that the methodology and information provided here may prove useful to those involved in performance-based design.

Table 7.13 shows the range of locations and building sizes included. Described in Figure 7.14 are the color scales used. Since each simulation produces its own high-to-low range, numerical comparison is only possible within each shape and location, not across ranges. For example, a good EUI in Omaha for a small H-shaped office is 40 kBtu/m^2/yr, whereas the good EUI of a large H-shape in Phoenix is 240 kBtu/m^2/yr. Therefore, each shape, location, and size presented in the pattern guide can only be compared within similar sizes or cities. Figures of small offices are at a 1:100 scale. The medium and large offices are at a 1:300 and 1:500 scale respectively. Given range of resultant geometries, as consistently as possible each shape type is presented, albeit a bit differently.

Table 7.13 **Outline of locations and office sizes shown in the pattern guide. Letter shapes of H, L, T, and U, including trapezoids (Trap), were randomly mixed and selected based on their performance results. Items noted with “X” identify cities where small, medium, and large shapes are present in the pattern guide.**

Office size	*Miami*	*New York*	*Omaha*	*Phoenix*
Small	X	X	X	X
Medium	X	X	X	X
Large	X	X	X	X

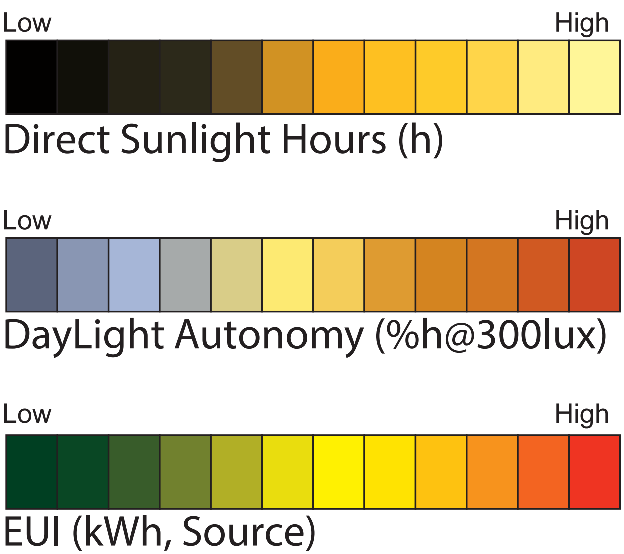


Figure 7.14 **The EUI (bottom), sDA (middle), and ASE (top) keys related to the visual outputs showing the colour range meaning presented in the pattern guide.**

Figure 7.15 Small office mixed shapes for Miami at 1:100 (approximate).

1 2 3 4

Figure 7.16 Small office mixed shapes for Miami at 1:100 (approximate).

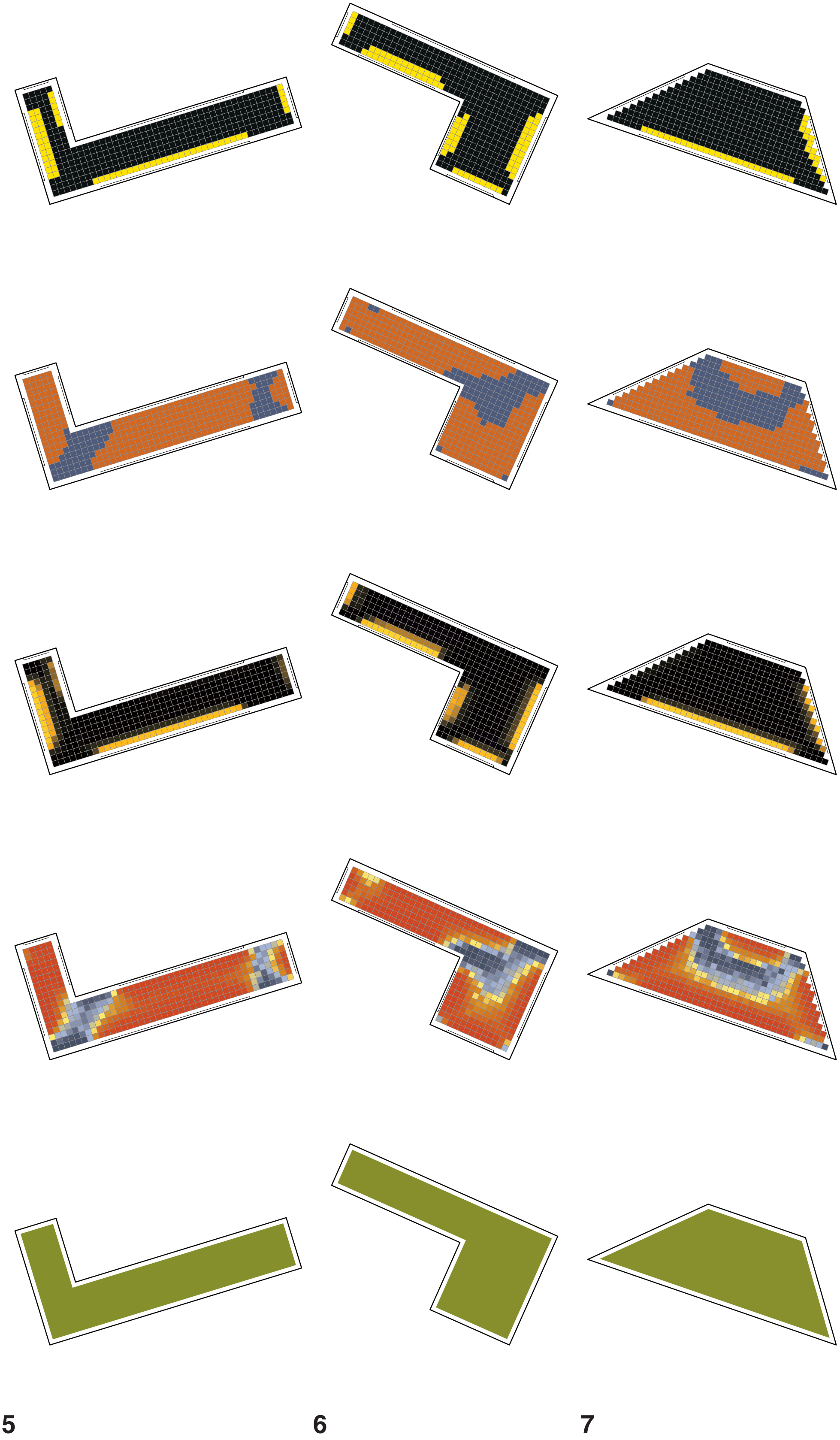


Figure 7.17 Small office mixed shapes for New York at 1:100 (approximate).

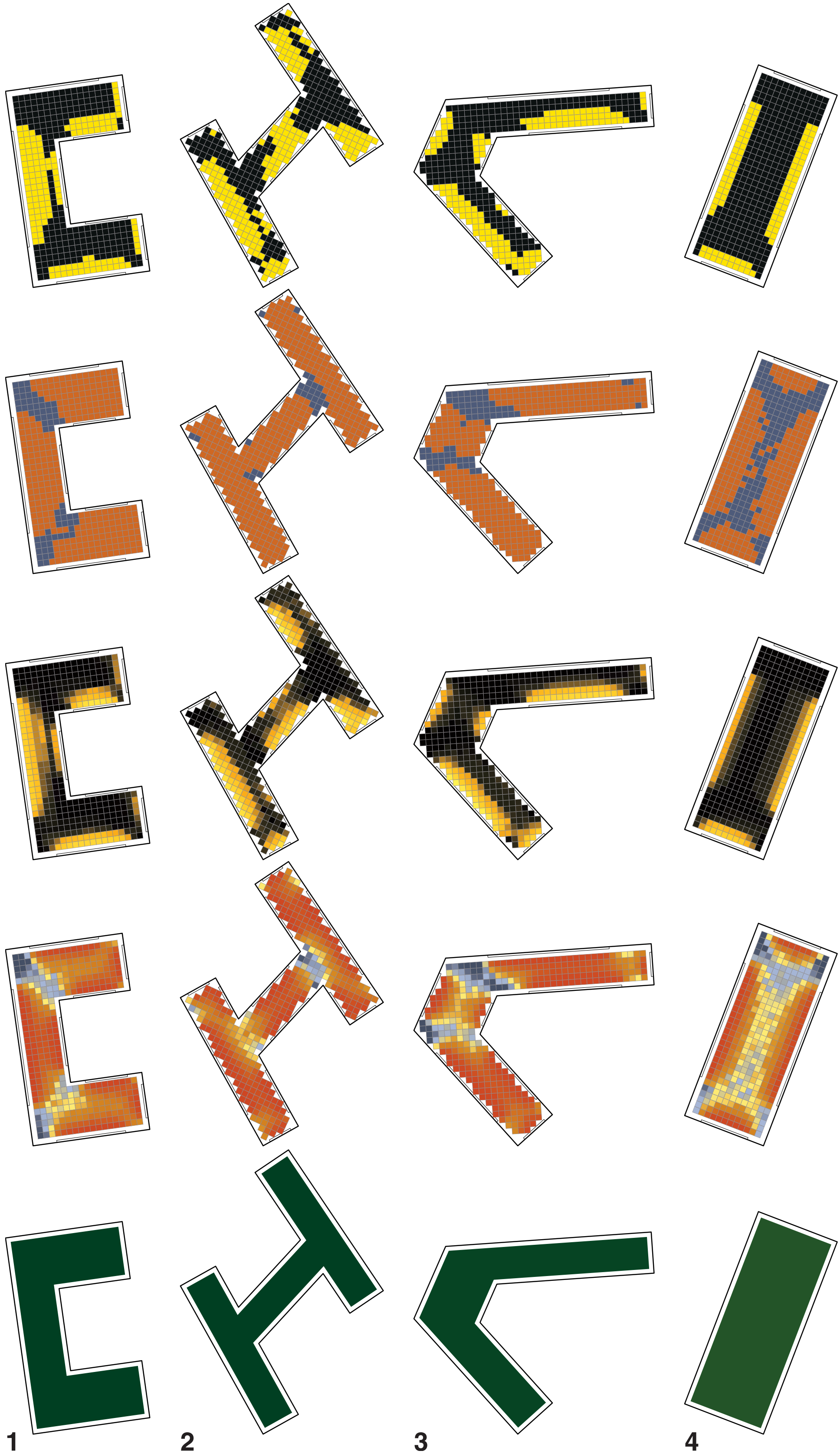


Figure 7.18 Small office mixed shapes for New York at 1:100 (approximate).

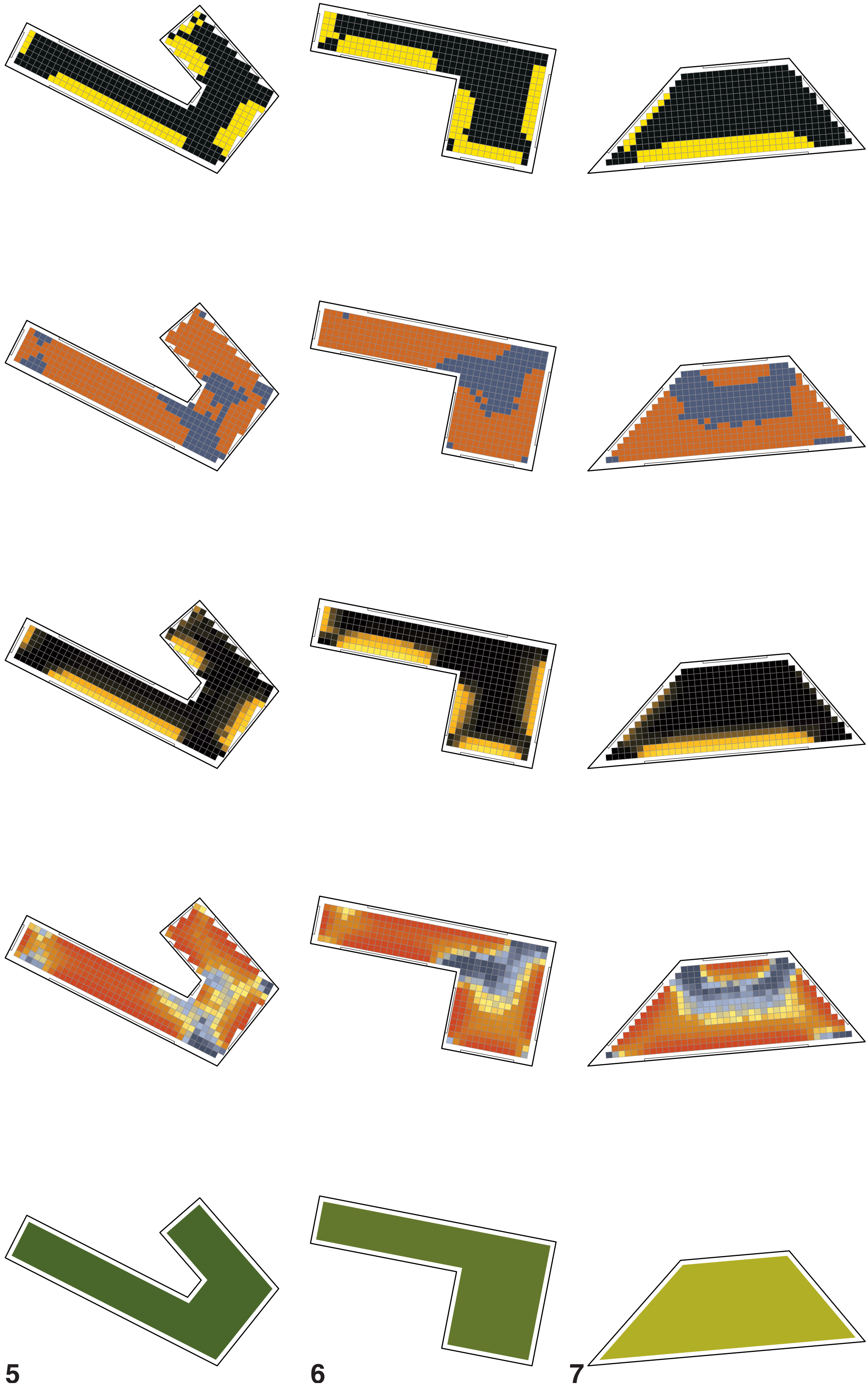


Figure 7.19 Small office mixed shapes for Omaha at 1:100 (approximate).

Figure 7.20 Small office mixed shapes for Omaha at 1:100 (approximate).

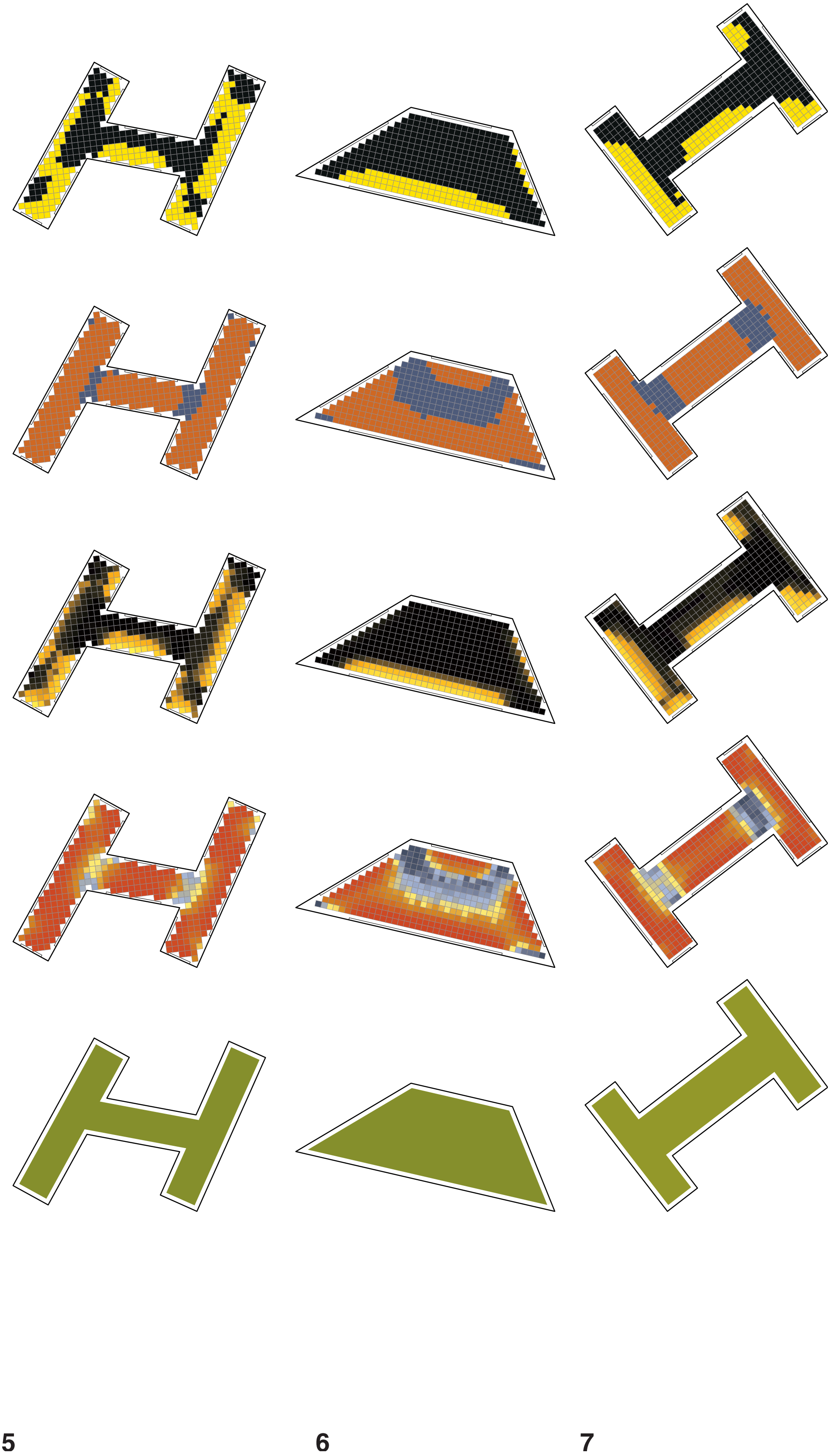


Figure 7.21 Small office mixed shapes for Phoenix at 1:100 (approximate).

Figure 7.22 Small office mixed shapes for Phoenix at 1:100 (approximate).

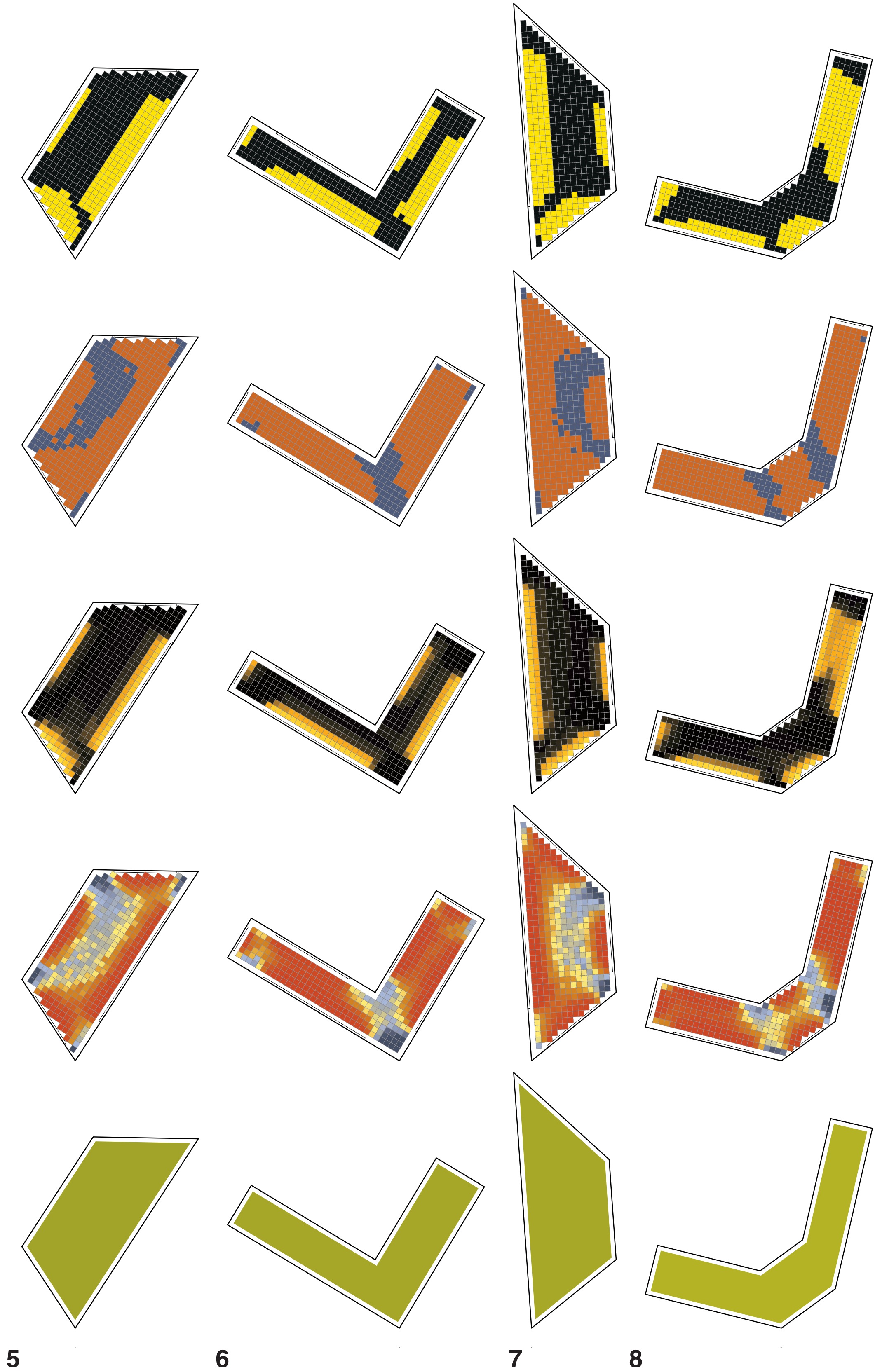


Figure 7.23 Medium office mixed shapes for Miami at 1:300 (approximate).

Figure 7.24 Medium office mixed shapes for Miami at 1:300 (approximate).

Figure 7.25 Medium office mixed shapes for New York at 1:300 (approximate).

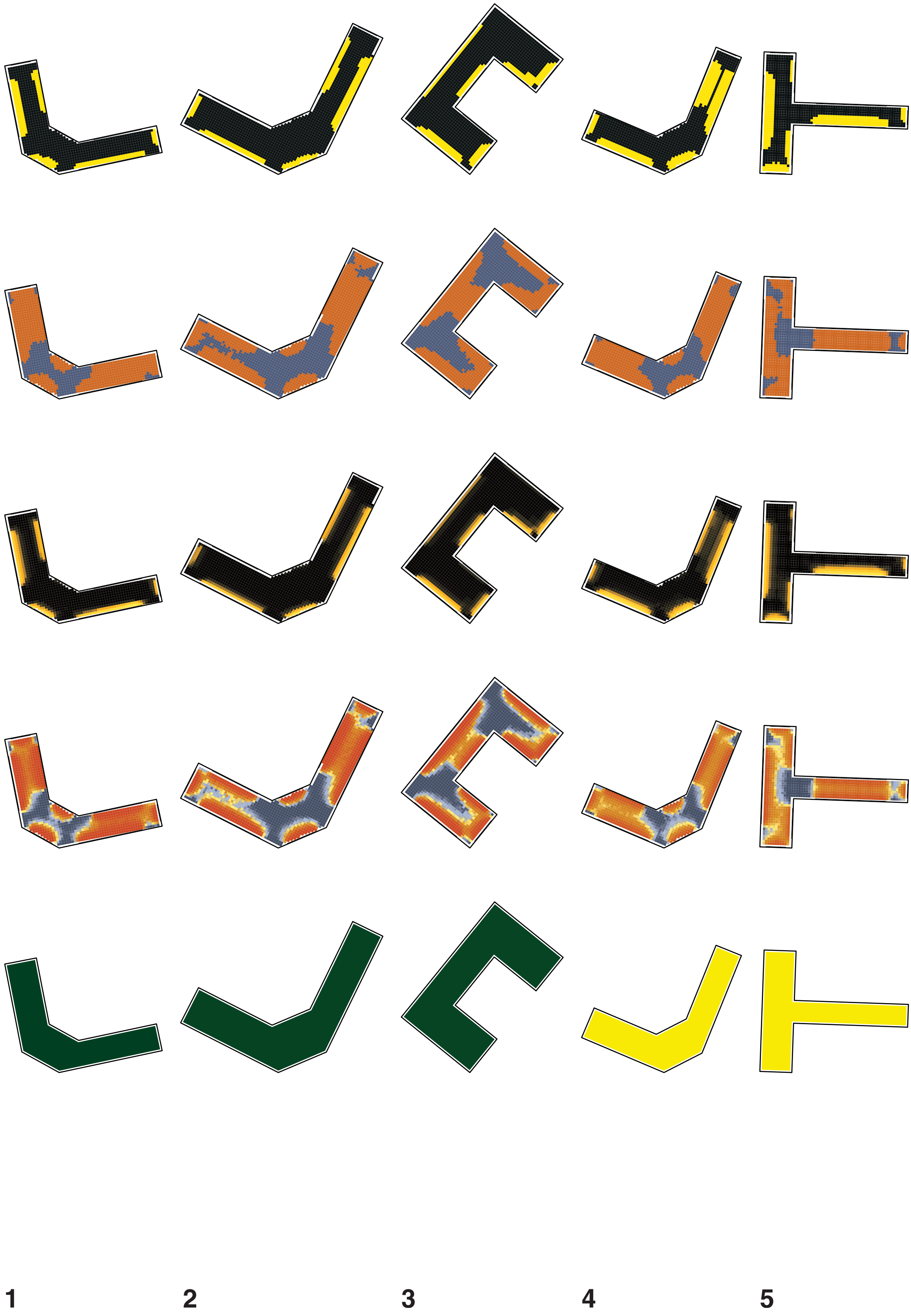


Figure 7.26 Medium office mixed shapes for New York at 1:300 (approximate).

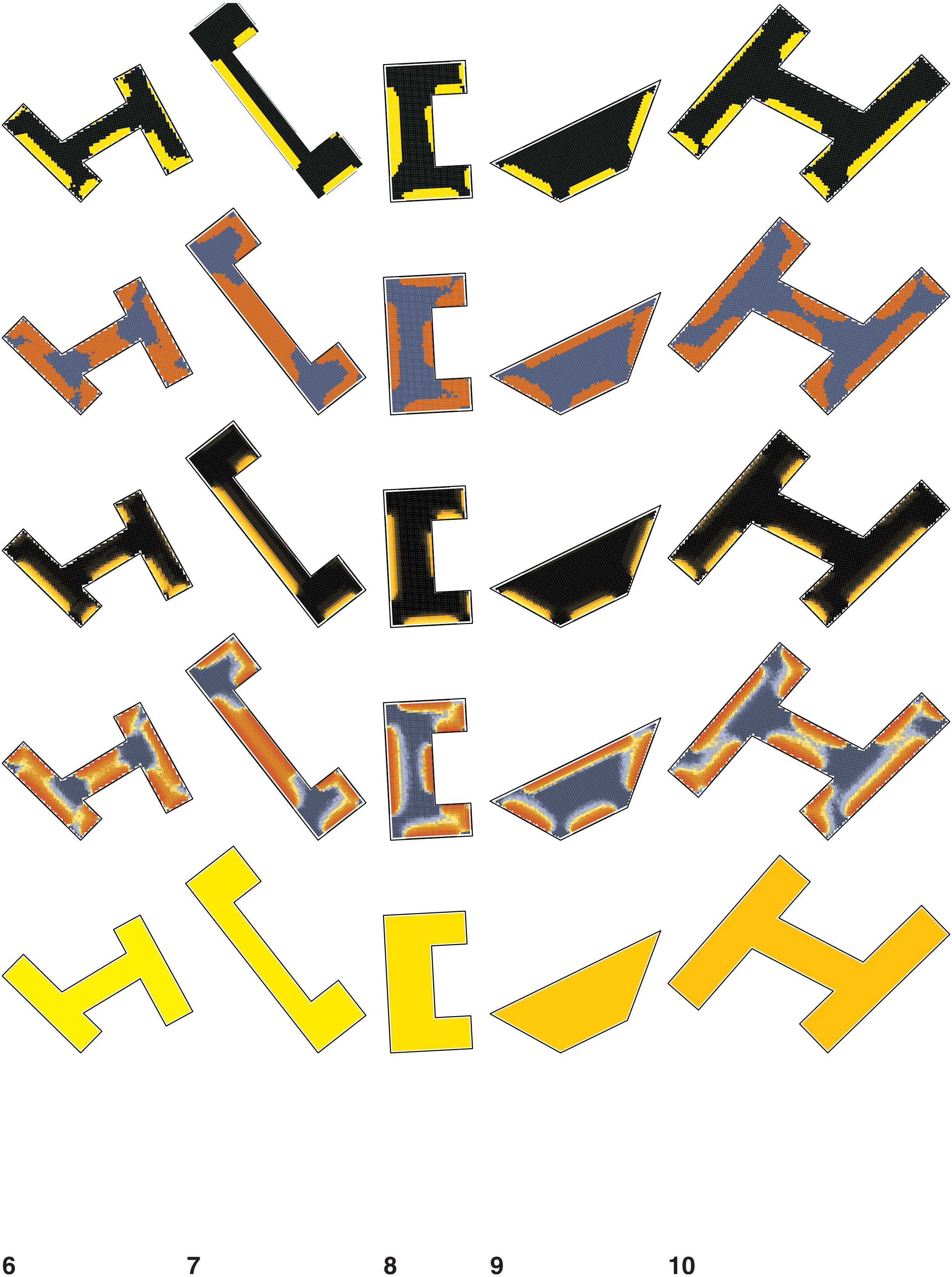
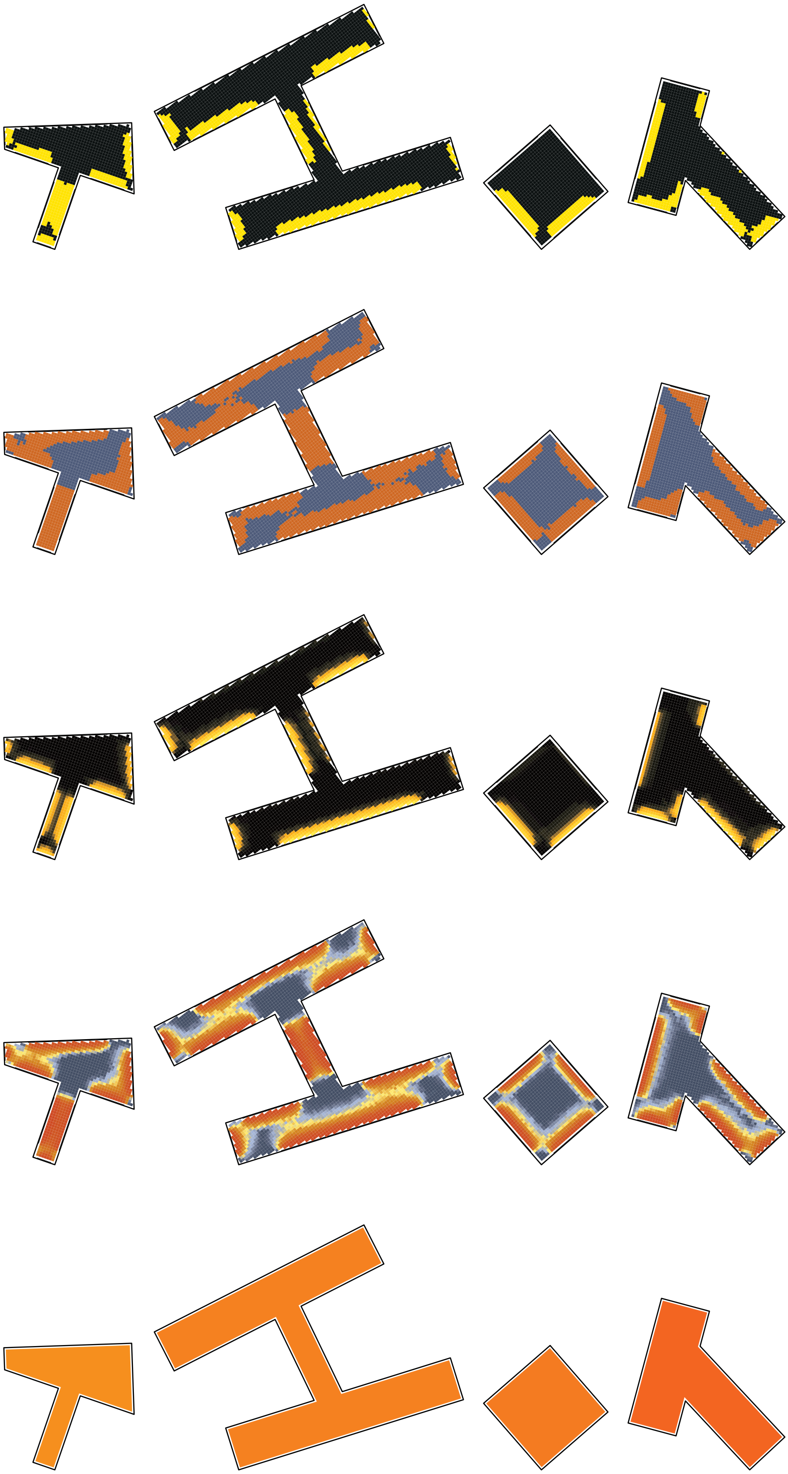


Figure 7.27 **Medium office mixed shapes for Omaha at 1:300 (approximate).**

1 2 3 4 5

Figure 7.28 Medium office mixed shapes for Omaha at 1:300 (approximate).



6 7 8 9

Figure 7.29 **Medium office mixed shapes for Phoenix at 1:300 (approximate).**

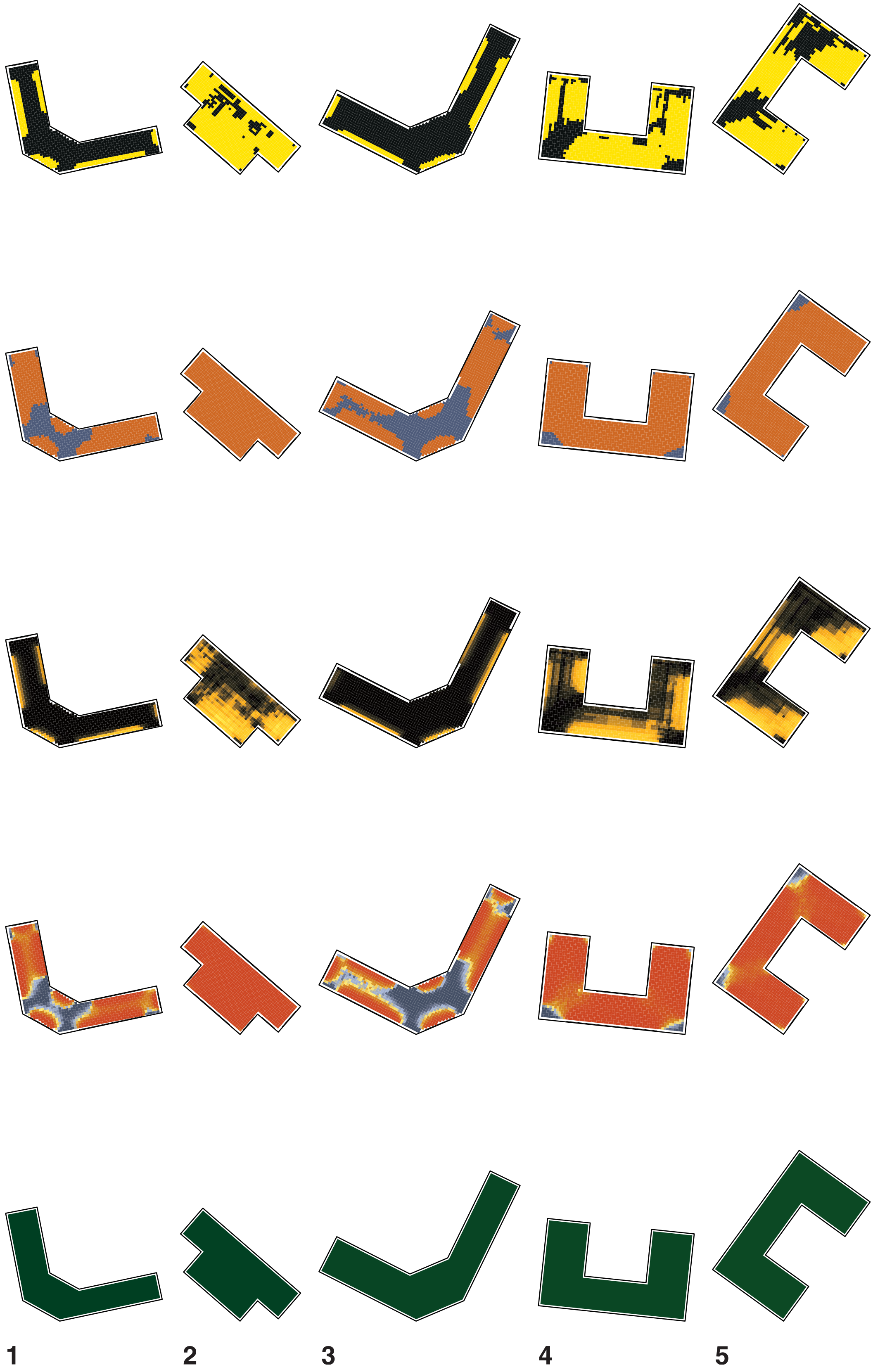


Figure 7.30 Medium office mixed shapes for Phoenix at 1:300 (approximate).

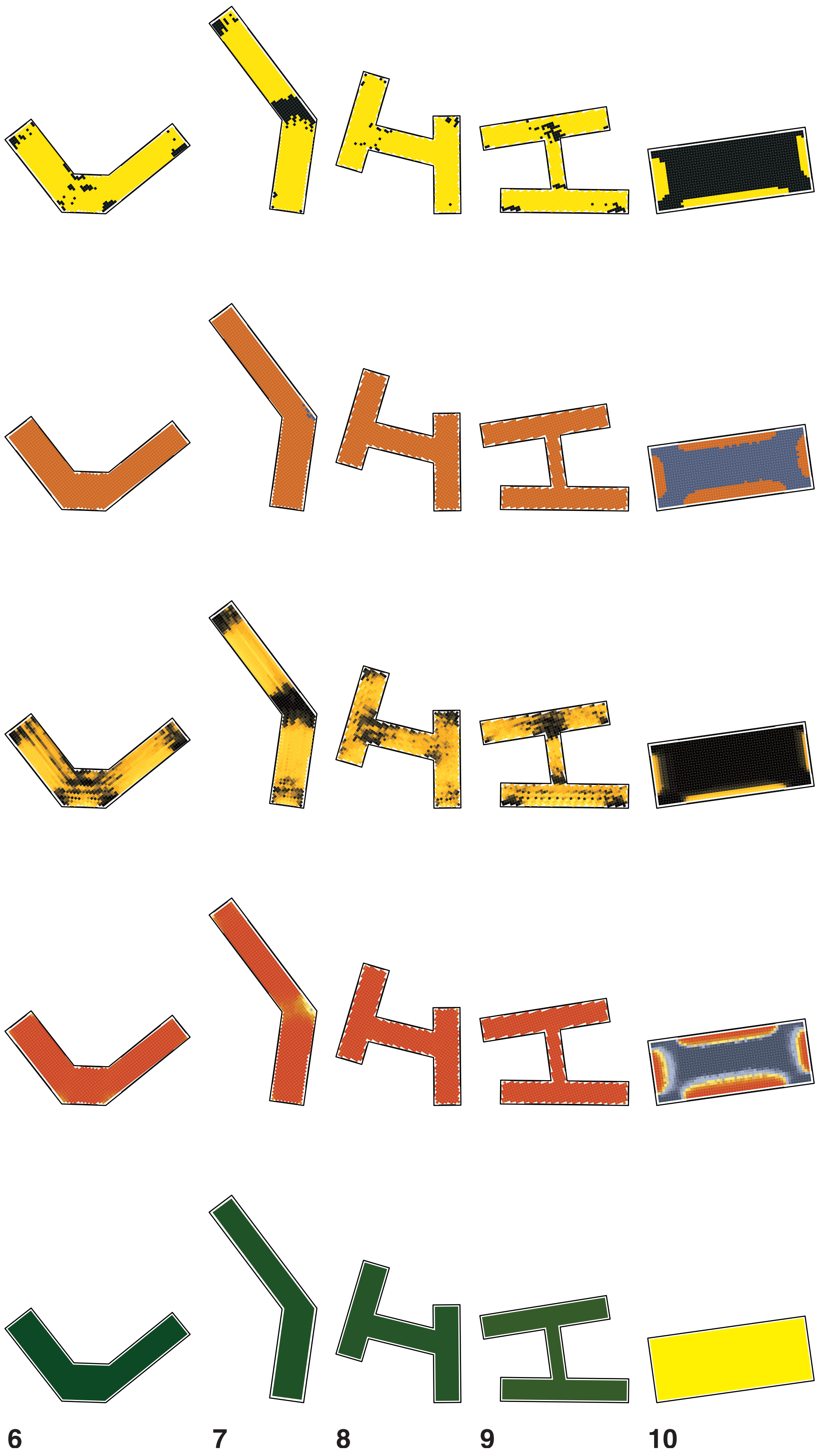


Figure 7.31 Large office mixed shapes for Miami at 1:500 (approximate).

Figure 7.32 Large office mixed shapes for Miami at 1:500 (approximate).

Figure 7.33 Large office mixed shapes for New York at 1:500 (approximate).

1 2 3 4 5 6

Figure 7.34 Large office mixed shapes for New York at 1:500 (approximate).

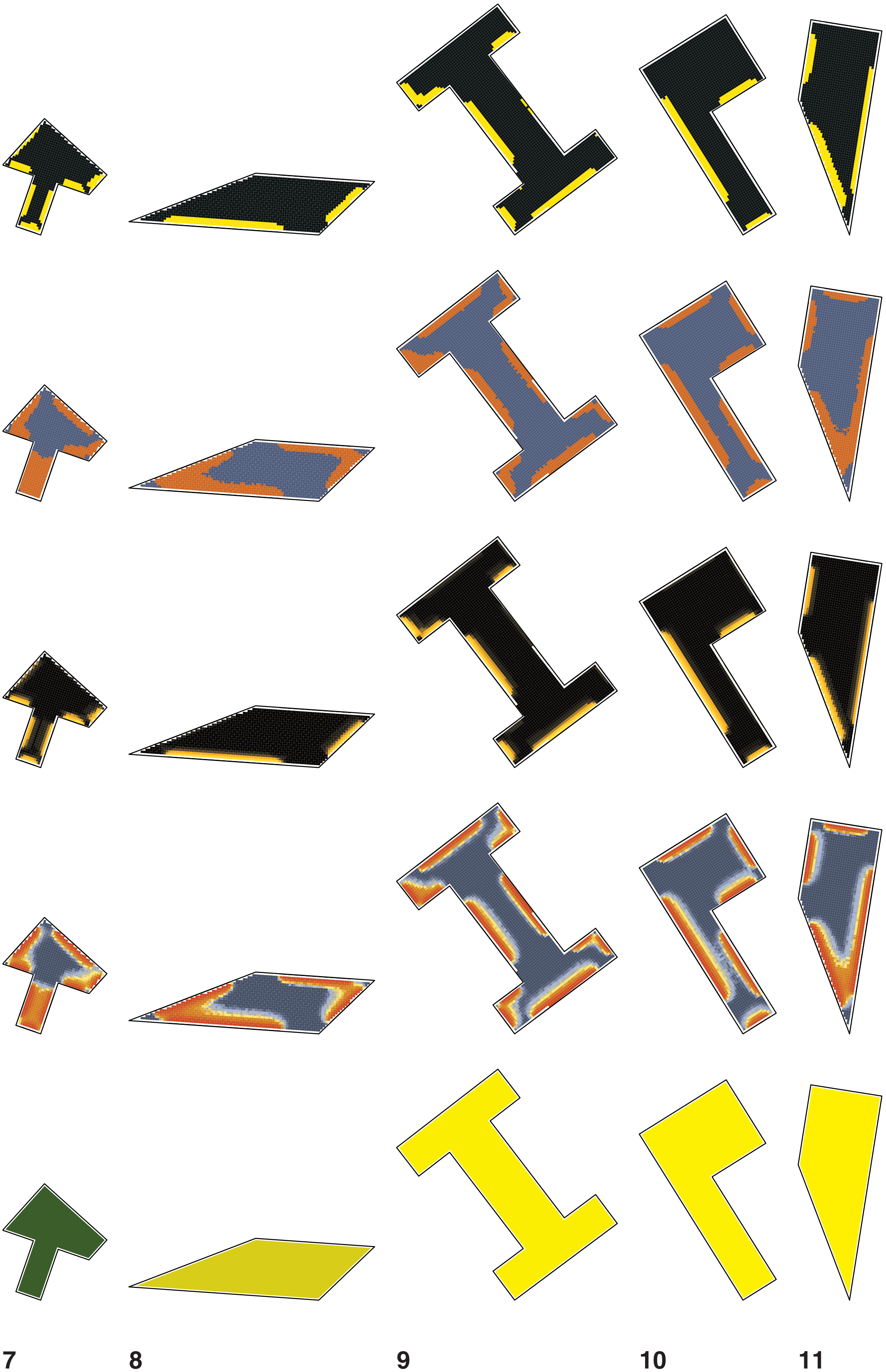


Figure 7.35 Large office mixed shapes for Omaha at 1:500 (approximate).

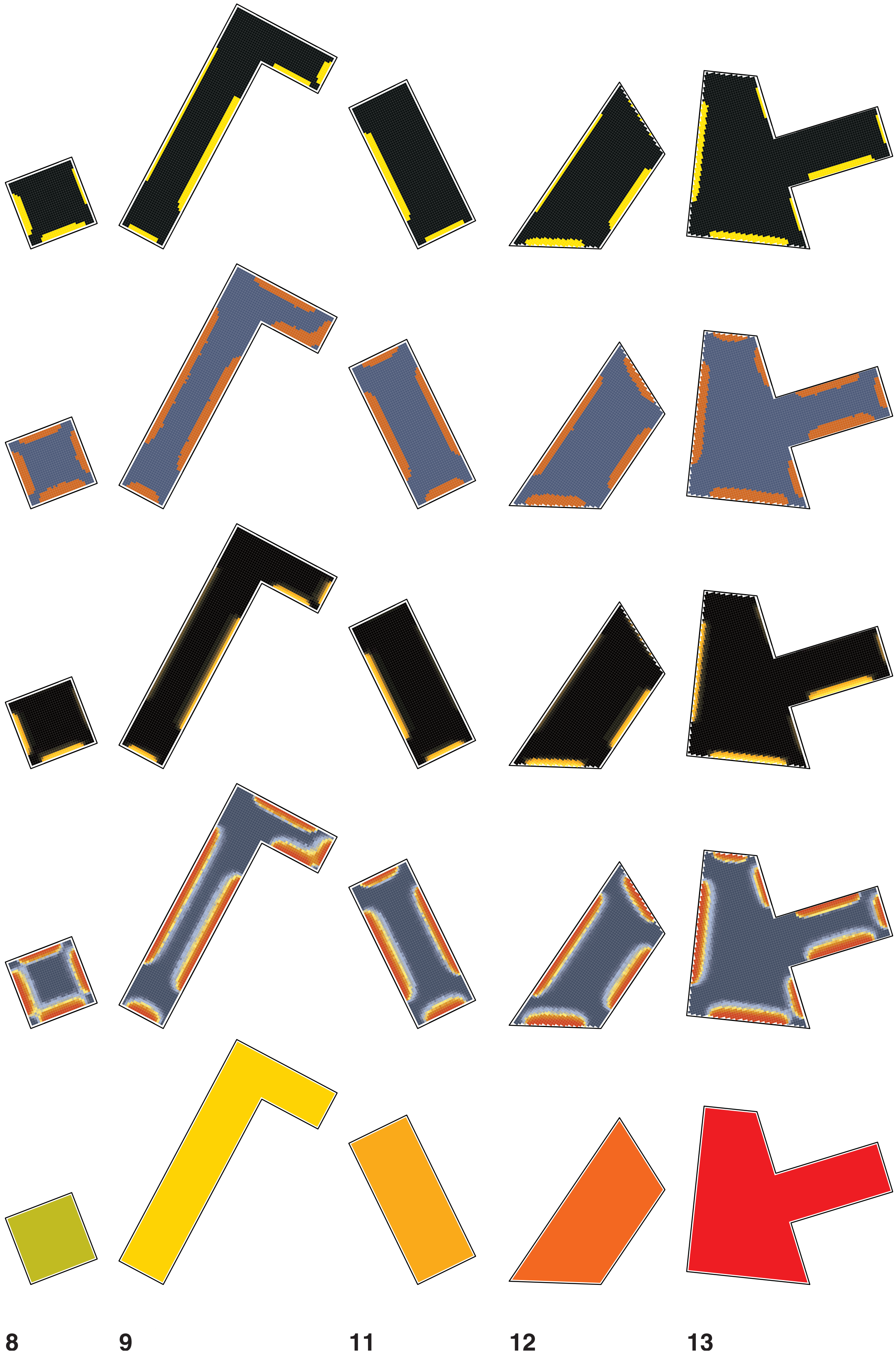


Figure 7.36 Large office mixed shapes for Omaha at 1:500 (approximate).

Figure 7.37 Large office mixed shapes for Phoenix at 1:500 (approximate).

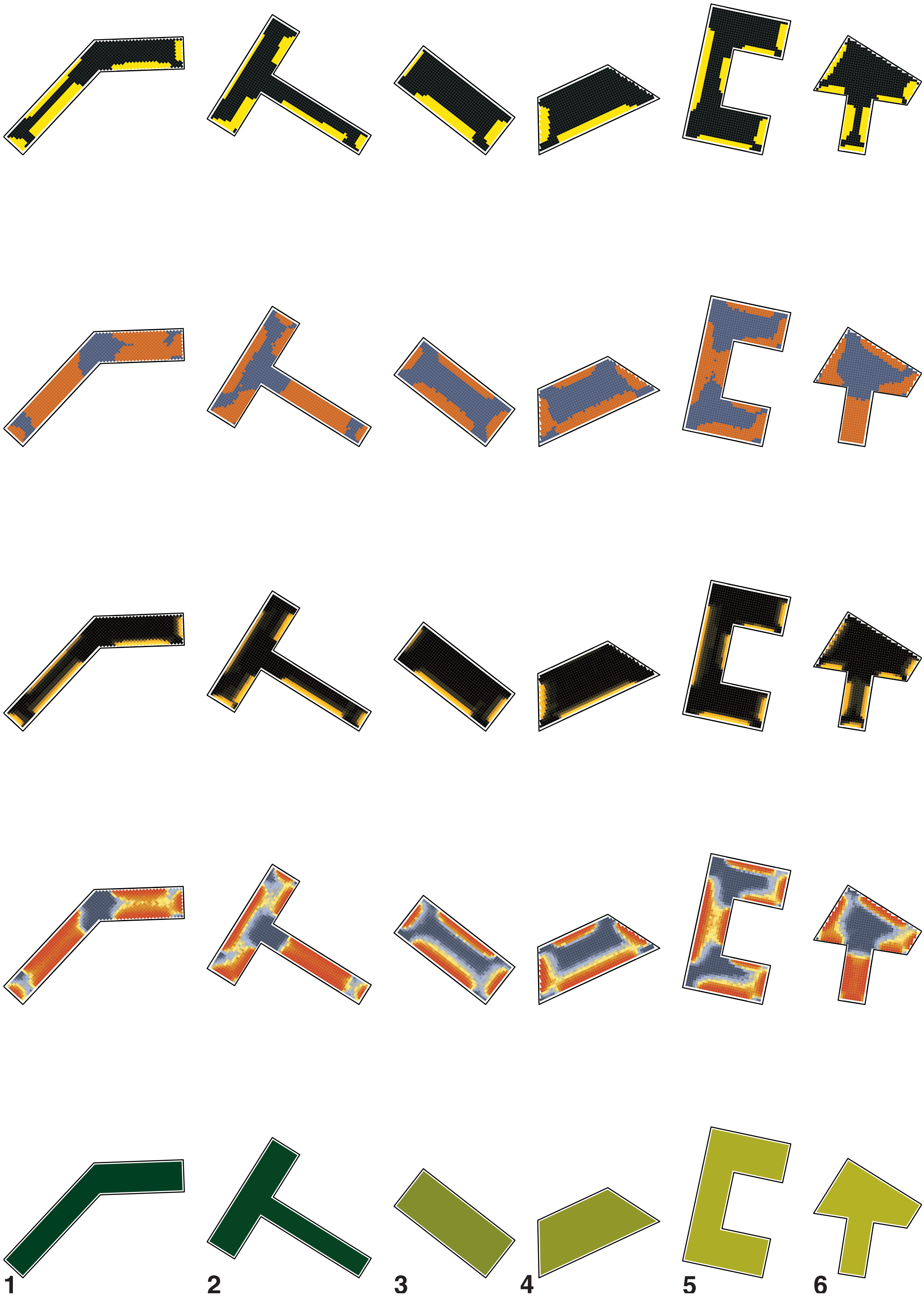


Figure 7.38 Large office mixed shapes for Phoenix at 1:500 (approximate).

Examples of whole-building models

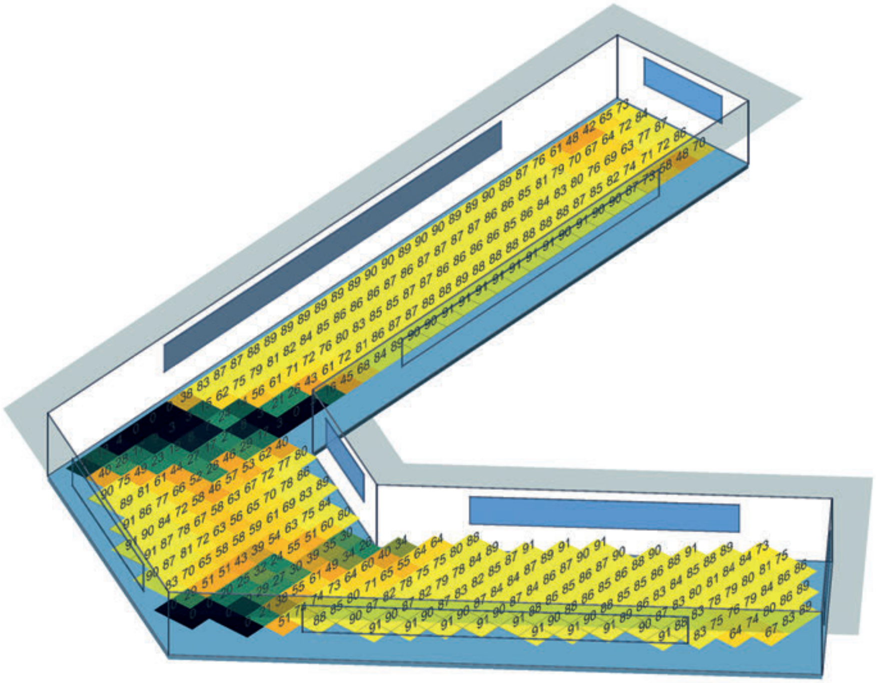


Figure 7.39
Axonometric view of a small U-shaped office in New York.

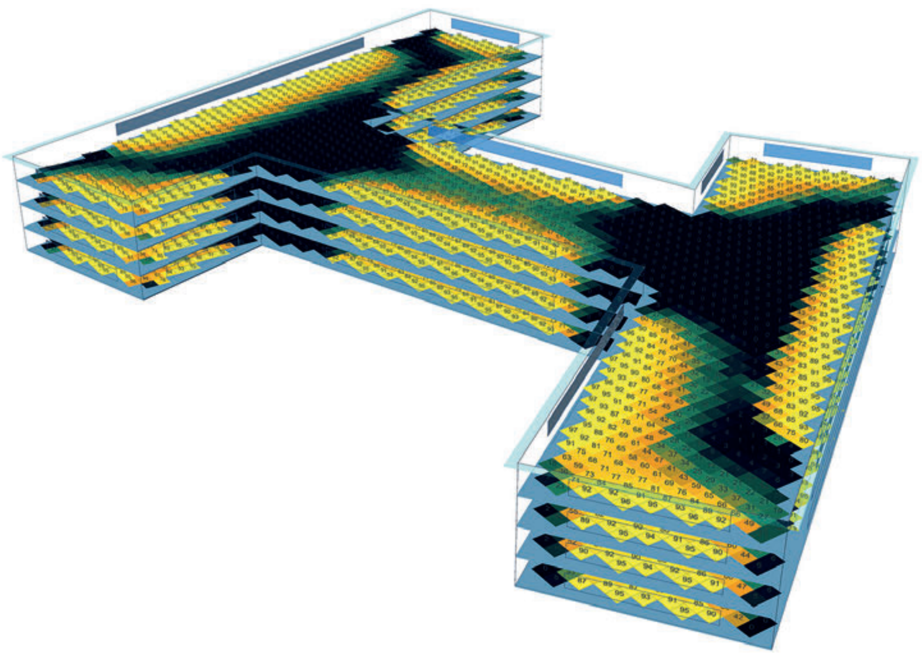


Figure 7.40
Axonometric view of a medium H-shaped office in New York.

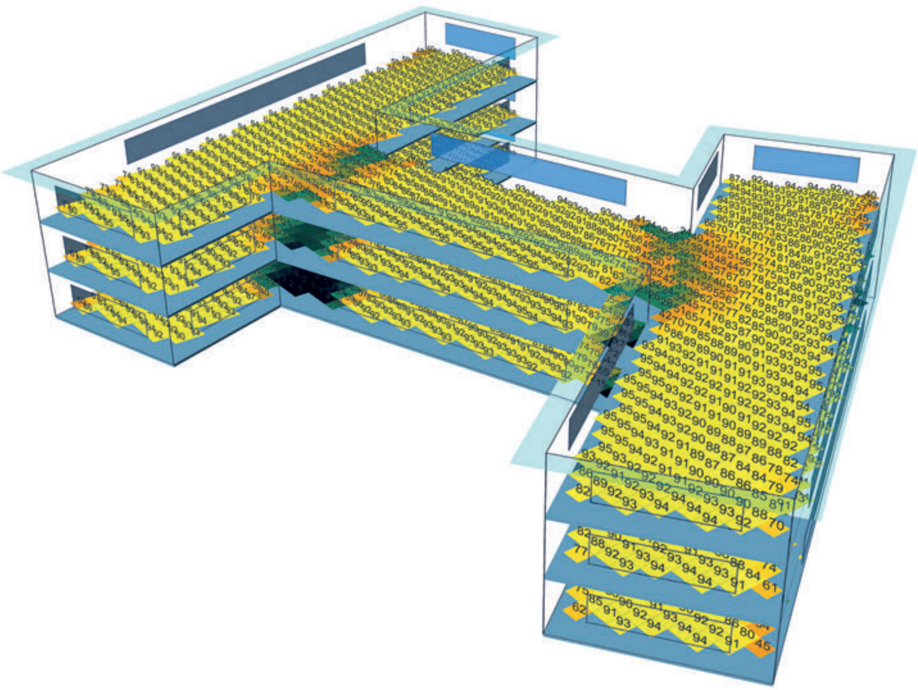


Figure 7.41
Axonometric view of a medium H-shaped office in Omaha.

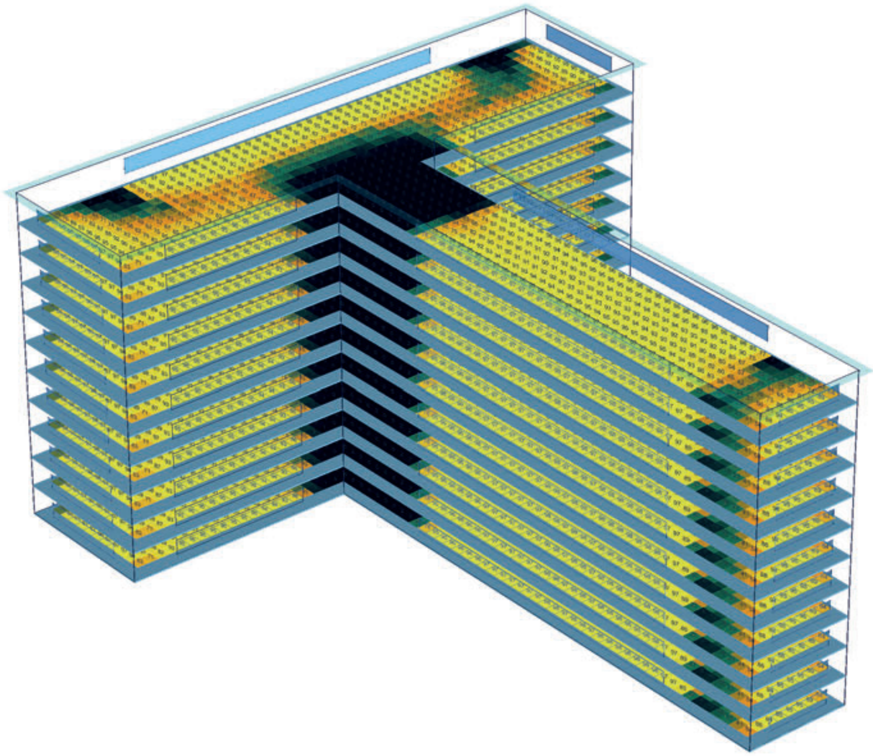


Figure 7.42
Axonometric view of a large T-shaped office in Miami.

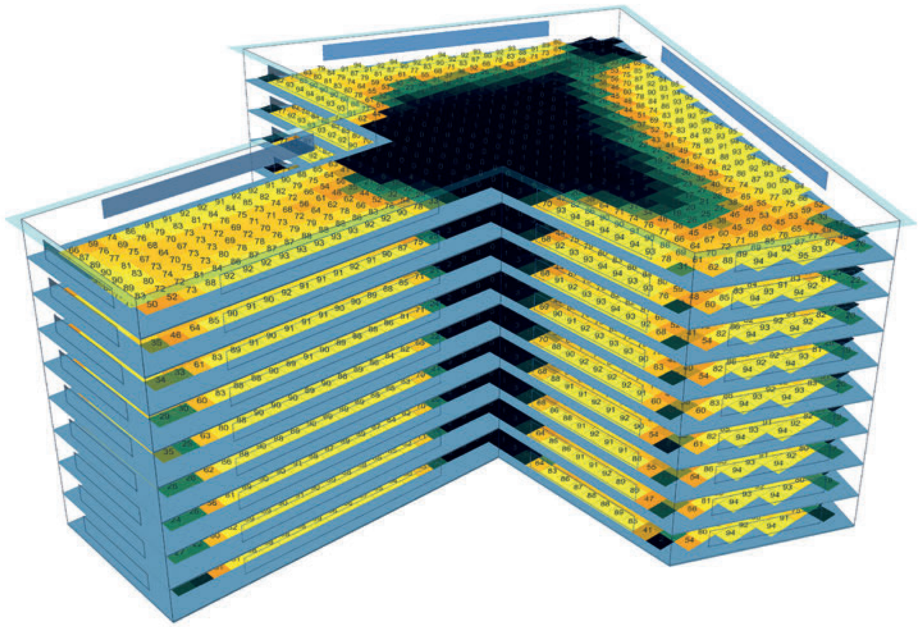


Figure 7.43
Axonometric view of a large T-shaped office in Omaha.

The End?

Not so fast. Our argument is that the energy performance and daylighting presented in the pattern guide are difficult to predict without the aid of simulation. The results of the pattern guide show how closely similar shapes may lead to very different results. Therefore, first the point is that it is hard to predict these tendencies with rules of thumb for daylighting (effective daylight depth is two times the height of the window). Second, linking daylighting and energy in one simulation result provides a more honest picture of the whole building's performance. This is what simulation is about: Providing more information than we had to begin with in order to make the best decision, whether we are using the BEM to understand, to compare, or to forecast the energy performance of our design decisions.

Daniel Overby discusses this on his blog with a post titled, "*Every Energy Model is Wrong—And Here is Why They are Indispensable*,"[14] and highlights that BEM is beneficial because now there is more information than before. Our process of discovery in this chapter highlights the deficiency of the existing BEM simulation methodologies. This entire book highlights our own research and explorations; therefore, the appropriate conclusion is that there is still much to learn, much to come in the future, and much more to explore using building energy and parametric modeling, scripting, and algorithms. This entire process comes in the pursuit of a new kind of built environment—that is, a carbon-neutral one.

Notes

1 Bernard Tschumi et al., "Introduction," in *Tschumi Le Fresnoy: Architecture In/Between* (New York, NY: The Monacelli Press, 1999), 9.
2 IES Daylight Metrics Committee, *Approved Method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE)*, IES. LM-83-12 (New York, NY: IES, 2012), 2.
3 Kyle Konis, Alejandro Gamas, and Karen Kensek, "Passive Performance and Building Form: An Optimization Framework for Early-Stage Design Support," *Solar Energy* 125 (2016): 161–179.
4 Ibid., 165.
5 Ibid., 173.
6 "performLive," http://performlive.com/design_brief.pdf.
7 RapidTables.com "Lux to watts calculator," www.rapidtables.com/calc/light/lux-to-watt-calculator.htm.
8 IES, *Approved Method*, 3.
9 Ibid., 4.
10 Since the study is executed in DIVA, the materials and compositions are also extracted from DIVA sources.
11 IES, *Approved Method*, 3.
12 Ibid.
13 To keep the results consistent, the technical report M. Deru and P. Torcellini, *Source Energy and Emission Factors for Energy Use in Buildings*, NREL/TP-550-38617 (Golden, CO: NREL, 2007) is used, which is also DIVA's source.
14 Daniel Overbey, "Every Energy Model is Wrong—And Here is Why They are Indispensable," August 5, 2016, http://danieloverbey.blogspot.com/2014/08/every-energy-model-is-wrong-and-here-is.html.

8 Project Examples

This chapter identifies and highlights energy modeling aspects of different projects that align with the goals of this book. We have collected a variety of project types and building sizes from a range of climate zones displaying disparate design strategies for small versus large buildings, skin-dominated versus internal-load dominated buildings, and for hot- versus cold-climate buildings (Table 8.1). The sustainability goals of many of these projects necessitated the use of energy modeling, and as such we have collected some basic information about these projects that would perhaps be of use to those beginning energy models for similar projects.

The geometric comparisons of these projects describe the built project and, when possible, how the design teams approached it (Table 8.2). For instance, a larger aspect ratio along with a higher WWR suggests that daylighting is a key design priority for a given project, whereas projects with a 1:1 aspect ratio and a lower WWR are typically found in colder climates and skin-dominated building types, such as in the residential and library projects. This range demonstrates the variability of a building's solution space, where one size certainly does not fit all.

Table 8.1 **Case study list.**

Project	*Type*	*Size (ft^2)*	*Location (climate zone)*	*Achievement*
Madison	Library	120,000	Madison, WI (6A)	LEED Gold Registered
Bullitt Center	Office	50,700	Seattle, WA (5B)	ZNE Certified
SAC	Office	94,000	Omaha, NE (5A)	None
La Casa	Multi-family	25,000	Washington, DC (4A)	LEED Gold Certified
DCHS	Office/Clinic	277,000	Durham, NC (4A)	LEED Gold Ready
350 Mission	Office	492,980	San Francisco, CA (3C)	LEED Platinum Registered
CNES	Lab	42,000	Atlanta, GA (3A)	LEED Platinum Certified
Fireside	Elementary	86,650	Phoenix, AZ (2A)	ZNE School
HPA	Lab	6,100	Hawaii (1A)	ZNE Certified

Table 8.2 **Geometric comparison.**

Project	*Dimensions (L × D × H)*	*Aspect ratio*	*F/E*	*EW/F*	*Cf*	*WWR %*
Madison	20' 11 3/16" × 132' × 62'	1.9	0.324	1.686	0.034	37
Bullitt Center	104' 6" × 99' 6" × 80'	1.05	1.24	0.62	0.048	40
SAC	236' × 98' × 60' 5"	2.41	1.25	0.51	0.049	46
La Casa	68' 4" × 63' 4" × 70'	1.01	1.18	0.71	0.046	26
DCHS	367' 10" × 359' 5" × 58' 5"	1.02	1.23	0.47	0.043	43
350 Mission	135' × 137' × 413'	1.01	0.43	2.15	0.032	76
CNES	218' × 122' 4" × 42'	1.78	0.68	0.75	0.05	48
Fireside	457' × 266' × 32'	1.72	1.074	0.37	0.009	9
HPA	105' × 80' × 20’	1.32	1.148	0.47	0.077	40

Madison Central Library

Figure 8.3 **Madison Central Library photograph © Lara Swimmer Photography.**

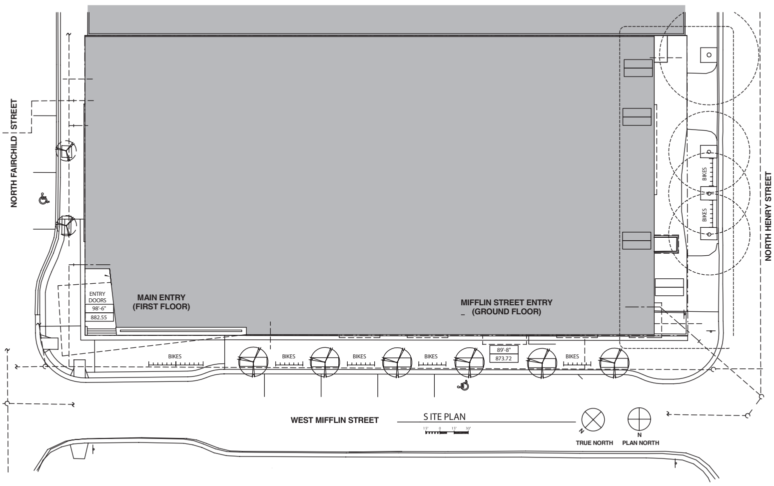


Figure 8.4 **Madison Central Library site plan © MSR Design.**

Building Summary

Project location: Madison, WI
Architect: MSR Design
Sustainable Engineering Group LLC
Meyer, Scherer & Rockcastle
Project type: library renovation and expansion
Project size: 95,000 ft^2 (renovation), 25,000 ft^2 (expansion) = 120,000 ft^2 (11,148 m^2)

Envelope Metrics

Dimensions above grade: 20' 11³⁄16" × 132' × 62'
Exterior wall area/floor area: (38,673/119,262ft^2) = 0.324
Floor area/(exterior wall area + roof area): (119,262/70738ft^2) = 1.686
Window–wall ratio: 0.317
Average exterior U-value (UA):

- Design Alt 1 roof = 0.033; wall = 0.165: 0.106 Btu/h/ft^2/°F
- Base Alt 2 Roof = 0.048; wall = 0.204: 0.134 Btu/h/ft^2/°F

Existing building (98,000 ft^2) EUI: 75.3 kBtu/ft^2
Simulated EUI: 55 kBtu/ft^2/yr
Actual EUI: 60 kBtu/ft^2/yr
Median library: 109 kBtu/ft^2/yr

Project Description[1]

Dilapidated, and located in a part of downtown considered by many residents to be unsafe, the Madison Central Library was neither well-used nor well-loved. The client's goals included reimagining how the library could provide service to all citizens and remain relevant as needs evolve. The design team completely transformed the 45-year-old building, creating a popular and vibrant community amenity that has spurred urban redevelopment. The addition of a third floor with a commons, gallery, and meeting rooms, along with gathering spaces throughout the building, created a cultural hub for Madison's citizens. Certified LEED-NC v3 Gold, the project features a green roof with on-site renewable energy provided by photovoltaic panels.

The daylit third-floor addition houses meeting rooms, an art gallery, and administrative offices, as well as a reading room and terrace that can be rented for private events. To accommodate after-hours events, custom-designed moveable wood screens can close off the library from the open atrium that leads to the third floor. Located throughout the library, glass-enclosed meeting rooms in a variety of sizes can be reserved for individual or group study and community meetings. Living room-like spaces on the first and second floors offer adequate lighting, comfortable seating, and plenty of integrated power and data plug-in points. Along with the library's community spaces, books, computers, iPads, and Wi-Fi access, patrons can also enjoy a new cafe and bookstore. Other amenities include a making space and a production lab—both of which offer opportunities for activities ranging from printmaking to stop-motion animation—with identities all of their own, and the teens' area offers space for study, play, and socializing. The bright and whimsical children's area evokes an open meadow, with vibrant colors, child-sized fixtures, and reading nooks that light up when a child crawls inside. While

the library interior was dark and inward-looking before the reconstruction, the former stack area shown here now houses the children's area. The previous exterior was dated and unfriendly, though the addition of windows now offers views into the library, visually opening it to the neighborhood, and the new glass atrium, large window openings, and changing LED-lit panels further create a vibrant civic presence for the downtown library.

Bullitt Center

Figure 8.5 **Bullitt Center photograph © Benjamin Benschneider/ OTTO.**

Building Summary

Project location: Seattle, WA
Architect: Miller Hull
Project type: office
Project size: 50,071 ft^2 (4,652 m^2)

Envelope Metrics

Dimensions above grade: 104.5' × 99.5' × 80'
Exterior wall area/floor area: 31,000/50,071 = 0.62
Floor area/(exterior wall area + roof area): (50,071/40,356) = 1.24
Window–wall ratio: 0.40
Average exterior U-value (UA): roof = 0.025; wall = 0.038 Btu/h/ft^2/°F
Simulated EUI: 15 kBtu/ft^2/yr
Actual EUI: 11 kBtu/ft^2/yr
Annual net EUI: –6.9 kBtu/ft^2/yr

Figure 8.6 **Bullitt Center site plan © The Miller Hull Partnership, LLP.**

Project Description[2]

The Bullitt Center is the first urban building of its kind and commonly regarded as "the greenest office building in the world." It represents the level of sustainability possible in a city setting, signifying a shift in the actual process of how buildings are designed, and demonstrates the range of opportunities for inventiveness and creativity that are possible when integrated design teams target aggressive efficiency goals.

The Bullitt Center takes cues from nature and has been compared to a living organism incorporating simplicity and efficiency in its interconnected systems. Design moves visually contribute to overall sustainable design goals and include open-concept floor plates with operable floor-to-ceiling windows for maximum daylighting and access to fresh air; heavy-timber framing—which has not been used in a downtown Seattle office building since the 1920s and was selected due to its prominence as a renewable regional material offering strength, beauty, and carbon sequestration; an "irresistible stair"—a transparent glass stairwell located on an outside wall of the building offering stunning views of the Seattle skyline to encourage occupants to walk among floors vs. taking an energy-drawing elevator inconvenienced by keycard access; highly efficient windows and fully automated exterior blinds which provide an interesting, layered façade while adjusting throughout the day; and most visibly, the overhanging photovoltaic panel array on the roof which provides all power for the building with a nod to Northwest regional design vernacular. While the building is state-of-the-art at the moment, the building technology, building envelope, and supporting structure are designed as separate components that can easily be updated to meet the needs of the next generation of users as advancements are made in coming years without seriously impacting other key aspects of the building.

SAC Federal Credit Union

Figure 8.7 **SAC Federal Credit Union photograph © Matt Deboer.**

Building Summary

Project location: Papillion, NE
Architect: Leo A. Daly
Project type: office
Project size: 94,000 ft^2 (8,733 m^2)

Envelope Metrics

Dimensions above grade: 236' × 98' × 60.4'
Exterior wall area/floor area: (43,365/85,489) = 0.507
Floor area/(exterior wall area + roof area): (85,489 /68,338) = 1.251
Window–wall ratio: 0.463
Average exterior U-value (UA): 0.129 Btu/h/ft^2/°F

Project Description[3]

SAC Federal Credit Union's Headquarters, designed by Leo A. Daly, is a four-story corporate office building located in Papillion, Nebraska. The overall size of the building is 94,000 GSF and includes a four-story connector atrium, retail branch, community room, fitness facility, and corporate training facility. The building was designed as

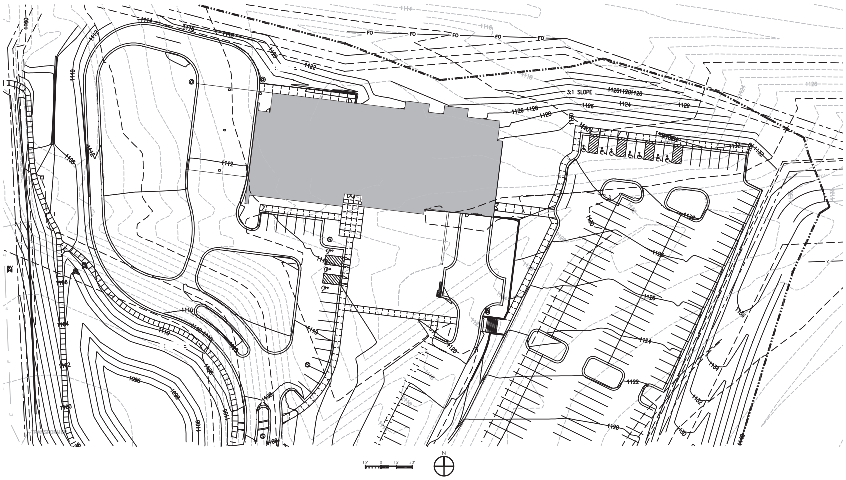


Figure 8.8 **SAC Federal Credit Union site plan © Leo A. Daly.**

a single-tenant building to accommodate up to 250 employees with a 50–50 mix of offices and workstations. Critical to SAC was that the design of the building reflect the Credit Union's commitment to its members, along with its grounded and progressive vision of their future. The building utilizes active chilled beams for convective cooling and has 218 geothermal wells spread throughout the site.

La Casa Housing

Figure 8.9 La Casa Housing photograph © Anice Hoachlander.

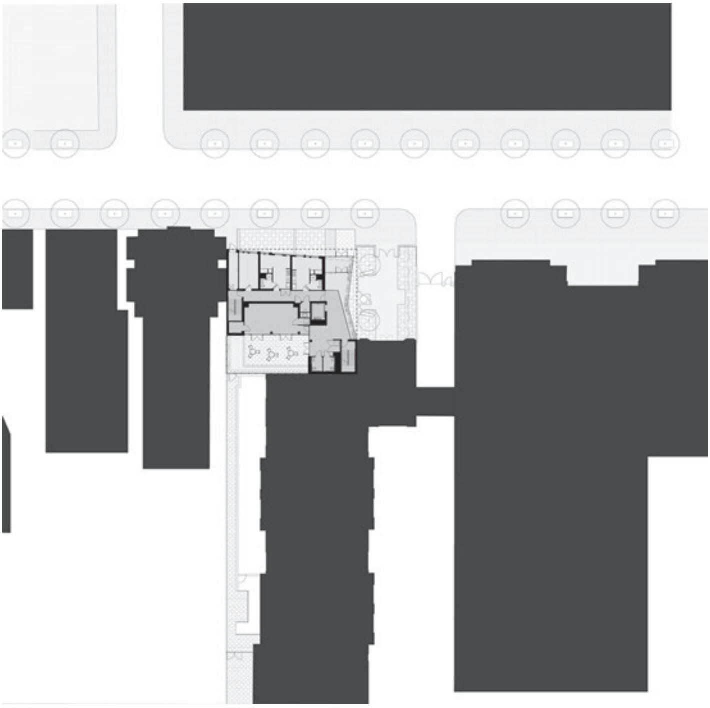


Figure 8.10 La Casa Housing site plan © Studio Twenty Seven.

Building Summary

Project location: Washington, DC
Architect: Studio Twenty Seven | Leo A. Daly joint venture
Project type: multi-family housing
Project size: 25,000 ft^2 (2,322 m^2)

Envelope Metrics

Dimensions above grade: 68.25' × 63.25' × 70'
Exterior wall area/floor area: 0.71
Floor area/(exterior wall area + roof area): 1.18
Window–wall ratio: 0.26
Average exterior U-value (UA): 0.15 Btu/h /ft^2/°F

Project Description

"La Casa" is the first new-construction permanent supportive housing project for the district's Department of Human Services.[4] "The District wants to break the notion that homeless care facilities are institutional, generic unpleasant places to be. . .. La Casa will change the perception of the public and the perception of the residents."[5] The project, designed in conjunction with joint-venture partner Leo A. Daly, consists of 40 single-occupancy living units with community and support spaces covering nearly 25,000 ft^2. The district currently operates a variety of housing types and models to accommodate the homeless, most of which focus on temporary nightly shelter. The La Casa Permanent Supportive Housing Project is the first to construct new private dwelling units, with full living spaces, kitchens, and baths for the chronically homeless. The project is currently in review for USGBC LEED Gold certification.[4]

The city wanted to redefine a homeless care paradigm that typically produces antiseptic institutional facilities. The architects were fortunate in having a municipal client that required design quality that would "meet and/or exceed" that of adjacent market-rate condominium buildings. As the first new-build permanent supportive housing facility in the city, La Casa is an important milestone for the district in its effort to redefine the concept of housing for the homeless community. In addition, the project maximizes the number of individual living units that can be accommodated on the small site.[4]

Crucial to its success as a supportive housing facility is the notion that La Casa residents experience it as a home rather than an institution. The living units are bright, simple, and efficient. Aperiodic floor-to-ceiling windows give each resident a unique perspective of the busy urban scape outside. Full kitchens and accessible bathrooms allow residents space to care for themselves, and the interior finishes

are durable but characteristically domestic—the warm grain of a wood floor, the brightness of colored tiles, or the weathered patina of exposed concrete are details that resonate with human perception.[6] Inspired by costlier studio loft apartments, each dwelling unit provides floor-to-ceiling operable windows for natural daylighting and ventilation, also designed for space efficiency and durability. The units offer functional simplicity, coupling a hybrid living, eating, and kitchen space with a sleeping niche. Each unit is fully ADA compliant.[7]

The site was a design challenge with strict parameters that predetermined the massing by the need to fit as many units as possible within the envelope defined by zoning. Building system and material decisions were driven by concerns for immediate and long-term cost, maintenance, technical performance, and the desire to achieve a LEED Gold rating. Both the client and the design team also recognized the project's potential to symbolize the city's plan of using supportive housing to address chronic homelessness.[8]

La Casa is an efficient and sustainable building that does not sacrifice open and active design. At the scale of the street, its façades bend in response to busy sidewalks and shaded pocket parks. Its two-story, fully-glazed lobby provides visual access to the interior, inviting passing community members to engage in the facility's mission. The irregular pattern of windows into the living units appear as dark voids during the day and projections of light at night, activating the building's regular form and shallow façade. The windows are framed by layers of cladding in low relief, and the energy of Irving Street imprints itself on the façade as a rippling gradient of light, intense at the building core and slowly fading to calm at the building edges.

The Studio Twenty Seven Architecture–Leo A. Daly team designed La Casa to inspire pride and a sense of community in its residents. It is a building that leverages the power of spatial autonomy with the context of a secure, supportive environment to encourage the rehabilitation of its residents. Not quite an apartment building, nor a dorm or shelter, La Casa is a new typology for housing the homeless.[6]

Durham County Human Services Complex

Figure 8.11
Durham County Human Services Complex exterior photograph © Mark Herboth.

Figure 8.12
Durham County Human Services Complex courtyard photograph © Mark Herboth.

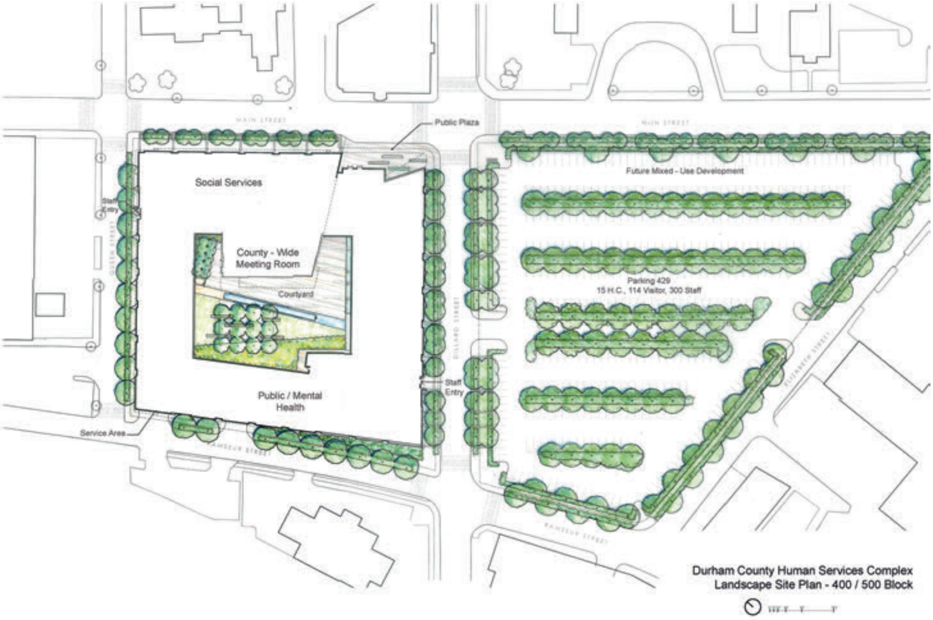


Figure 8.13 Durham County Human Services Complex site plan © Perkins Will – Architect and Surface 678 – Landscape Architect.

Building Summary

Project location: Durham, NC
Architect: Perkins and Will
Project type: office/clinic
Project size: 277,000 ft^2 (25,734 m^2)

Envelope Metrics

Dimensions above grade: 367' 10" × 359' 5" × 58' 5" average height
Exterior wall area/floor area: (130,100/277,000) = 0.47
Floor area/(exterior wall area + roof area): 1.23
Window–wall ratio: 0.43 (courtyard 0.54)
Average exterior U-value (UA):

- Wall = 0.053 Btu/h/ft^2/°F
- Roof = 0.041 Btu/h/ft^2/°F

Project Description

The new Durham County Human Services Complex houses the consolidation of the county's Social Services, Public Health, and Mental Health departments, along

with a new countywide meeting space. These agencies often serve the same clients, who benefit from the improvement in the delivery of Human Services through conveniently located facilities. The project, located in the East Main Street corridor of downtown Durham, represents an important first step and catalyst toward the revitalization of this underdeveloped part of downtown.

Built in two phases, the three-story, 277,000 ft^2 building includes 102,000 ft^2 of health and dental clinic, pharmacy, lab, administrative office, and support space for the Department of Public Health. Office area, conference rooms, and training rooms are provided for the Departments of Social Services and Mental Health across approximately 160,000 ft^2. The 15,000 ft^2 countywide use area accommodates a large 500-seat multipurpose space.

The building's façade is intentionally brought to the edges of the block, forming an O-shaped plan with a large public courtyard at the center of the complex. All façades front their respective streets to give the building an urban presence, while the internalized courtyard becomes a gem within the urban setting. The plan, with its relatively narrow floorplates and main circulation facing the inner courtyard, allows for both generous daylighting and exterior views from the building.

Sustainability principles drove the design of the project. At one level, the building speaks to environmental responsibility through its planned USGBC LEED Gold certification, while it additionally facilitates the delivery of the crucial human services that help sustain individuals and families with the greatest need. The complex responds to the needs of the community not only by meeting the functional requirements of the building program, but also by providing high-quality exterior and interior environments that engender civic pride.[9]

Significant attributes of this project include cisterns to collect rainwater from the roof and condensate from mechanical equipment to provide 100 percent of water for irrigation needs. The project in pursuing LEED anticipates saving 27 percent of energy use. In part these savings are due to a high efficiency underfloor air distribution mechanical system throughout most of the building; daylight and occupancy sensors along with dimmable ballasts/light fixtures work in conjunction with daylight systems to dramatically reduce lighting and heating costs; curtainwall systems include exterior sunshades and high-performance glazing; and roof monitors provide daylight to second and third floors while light-shelves at the typical curtainwall help push daylight deeper into the building.

350 Mission Street

Figure 8.14 350 Mission Street exterior rendering plan © 2016 Skidmore, Owings & Merrill LLP.

Figure 8.15 350 Mission Street site plan © 2016 Skidmore, Owings & Merrill LLP.

Project Summary

Project location: 350 Mission St., San Francisco, CA
Architect: Skidmore, Owings & Merrill LLP
Building type: high-rise office building
Building size: 492,980 ft^2 (45,799 m^2)

Envelope Metrics

Dimensions above grade: 135' × 137' × 413' to top of crown (384' to roof deck)
Exterior wall area/floor area: 0.43
Floor area/(exterior wall area + roof area): 2.15
Window–wall ratio: 0.765
Average exterior U-value (UA): U = 0.503 Btu/h/ft^2/°F; SHGC = 0.33
Simulated EUI: 134 kBtu/ft^2/yr
Actual EUI: 91 kBtu/ft^2/yr

Project Description

The design of 350 Mission, a LEED Platinum-certified office building in downtown San Francisco, was driven not only by rigorous environmental performance goals, but also by the desire to stimulate social engagement. In generating the tower's form, structure, and building systems, SOM reexamined standards long taken for granted by developers in order to reinvent a ubiquitous building type.

350 Mission contributes to the life of its immediate surroundings with a transparent 50-foot-tall lobby that opens up to the street. Dubbed an "urban living room," the corner of the lobby features a dramatic cantilever with 90 feet of glass panels that slide open and closed—joining the lobby to the street and blurring the threshold between the public and private realms. The lobby includes a cafe and restaurant, amphitheater seating, and space that can be configured for pop-up events. Overhead, a commissioned work of digital art animates a 70-by-38-foot LED screen that, visible from the street, engages and invites people into the urban living room where they can meet up, socialize, work together, or simply relax.

The urban living room is an experiment in the serendipitous and meaningful interactions that occur in great cities. Its results will influence a growing body of research into contemporary workplaces—the popularity of casual work environments as well as the productivity of creative collision.

The design of 350 Mission's tenant space channels that spirit. The 30-story volume embodies the higher workforce densities and flexible space planning of contemporary offices, with a highly innovative system of long-span concrete slabs. In addition to allowing greater interaction between occupants, the engineering, combined with underfloor air and power distribution, maximizes perimeter glass. Using ultra-thin concrete instead of steel also helps 350 Mission achieve more daylight while increasing overhead space for employees.[10]

The 350 Mission 30-story office tower encompasses a variety of sustainability strategies that will cut energy costs by about one-third. The building's cladding contains high-performance, insulated glass units that reduce solar heat gain yet maximize visibility. The façade conveys a "woven" pattern in which alternating outward-tipping panels reflect sky brightness and inward-tipping panels are in contrasting shade. This pattern culminates at the skyline with feathery luminescent scrims placed behind the glass.

The sustainability agenda for 350 Mission underscores an aspiration to reinvent the speculative office paradigm. In addition to daylighting and zoned underfloor HVAC distribution, the project features rainwater harvesting and graywater recycling for non-potable uses. The design allocates space for bicycle storage and charging stations for electric vehicles. A video wall in the lobby will publicly display energy usage, embedded carbon, and other building performance metrics. Once the building is ready for occupancy, tenants will be encouraged to support sustainable practices.[11]

Carbon Neutral Energy Solutions Laboratory

Figure 8.16 **Carbon Neutral Energy Solutions Laboratory photograph © 2016 Jonathan Hilyer.**

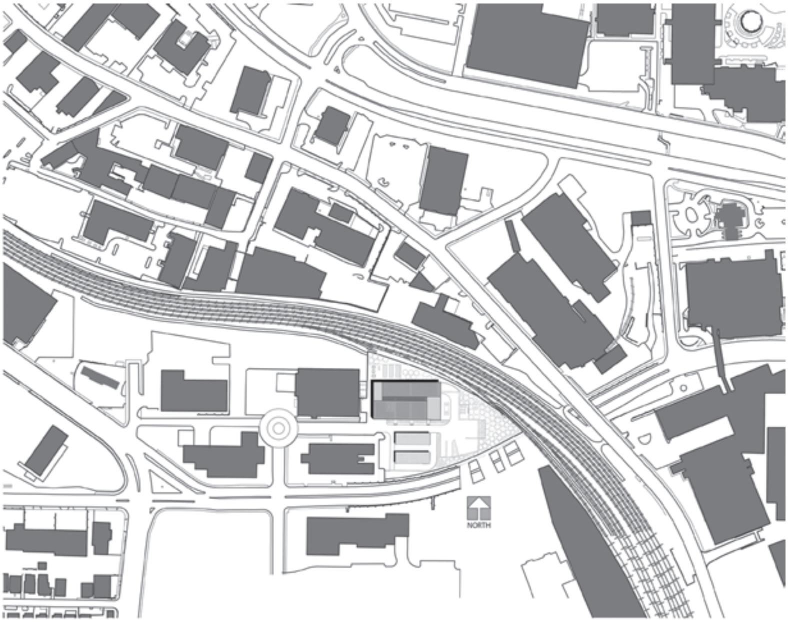


Figure 8.17 **Carbon Neutral Energy Solutions Laboratory site plan © 2016 HDR, Inc.**

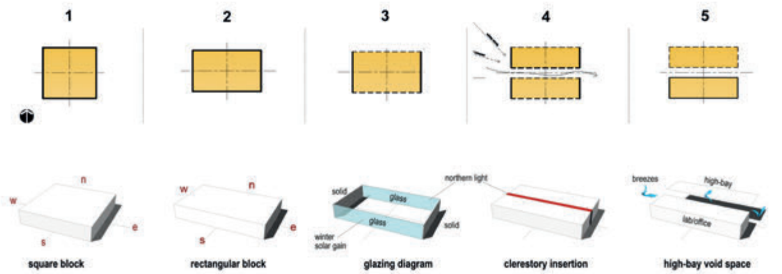


Figure 8.18 **Carbon Neutral Energy Solutions Laboratory diagram © 2016 HDR, Inc.**

Building Summary

Project location: Atlanta, GA
Architect: HDR
Project type: research laboratory
Project size: 42,000 ft^2 (3,902 m^2)

Envelope Metrics

Dimensions: 218' × 122' 4" × 42'
Exterior wall area/floor area: (29,000/38,320) = 0.75
Floor area/(exterior wall area + roof area): (38,320/56,500) = 0.68
Window–wall ratio: 0.48 (6150 ft^2 of Kalwall is counted as window)
Average exterior U-value (UA):

- Wall = 0.064 Btu/h/ft^2/°F
- Roof = 0.032 Btu/h/ft^2/°F

Simulated EUI: 29 kBtu/ft^2/yr

Project Description[12]

Georgia Tech's new 42,000 gross square-foot CNES laboratory allows project-based experiments of varying durations to be rapidly modified in a non-traditional environment. The laboratory is a center for research dedicated to carbon-neutral energy conversion technologies including combustion, gasification, and biochemical-enzymatic conversion of biomass and carbon-dioxide capture. The facility enables collaboration with industry partners focused on energy conversion technologies. CNES enables researchers to evaluate laboratory results at bench- or pilot-scale. The results are expected to lead to technologies that can then be scaled further to meet the needs of research sponsors. The shop-like facility utilizes a clear three-part organization of high-bay, mid-bay, and computational labs and offices to provide flexibility. Each area is focused on supporting specific research requirements. Such an arrangement allows companies investing in CNES-based research to test new concepts before deciding on larger investments. The laboratory achieved LEED Platinum certification.

The CNES Laboratory is itself a research project focused on carbon-neutral energy research. The laboratory is intended to set a new standard for the sustainable design of buildings of its type by optimizing passive energy technologies, reducing energy demand, and maximizing its use of renewable energy. The building is intended to act as a prototype living and learning laboratory, and to offer lessons learned for future net-zero attempts. Its energy strategies have been well

documented and are being tracked by Georgia Tech's CNES dashboard, located in the building lobby. The dashboard monitors energy use and production in the building, and is used as an educational tool. The facility has already been used as a case study for two graduate-level courses at Georgia Tech related to energy-efficient building design.

The CNES Lab sets a new standard for high-performance sustainable design by optimizing passive energy technologies, reducing electrical demand, and maximizing the use of renewable energy. The project is a design–build collaboration (integrated project delivery) between Georgia Tech, HDR, and Gilbane, with all team members on board on day 1. This collaboration was critical to effectively meet the goals of a rational no-frills design, maximum flexibility, and net-zero site-energy. The project's goals inspired the team to achieve a straightforward and adaptable design with an unparalleled level of energy efficiency for a building of this type. In addition to maximizing energy efficiency, the design addressed significant sustainability issues, including site ecology, water conservation, material selection, and greening of the hard-pack site.

Fireside Elementary

Figure 8.19 Fireside Elementary photograph © 2016 CORE Construction.

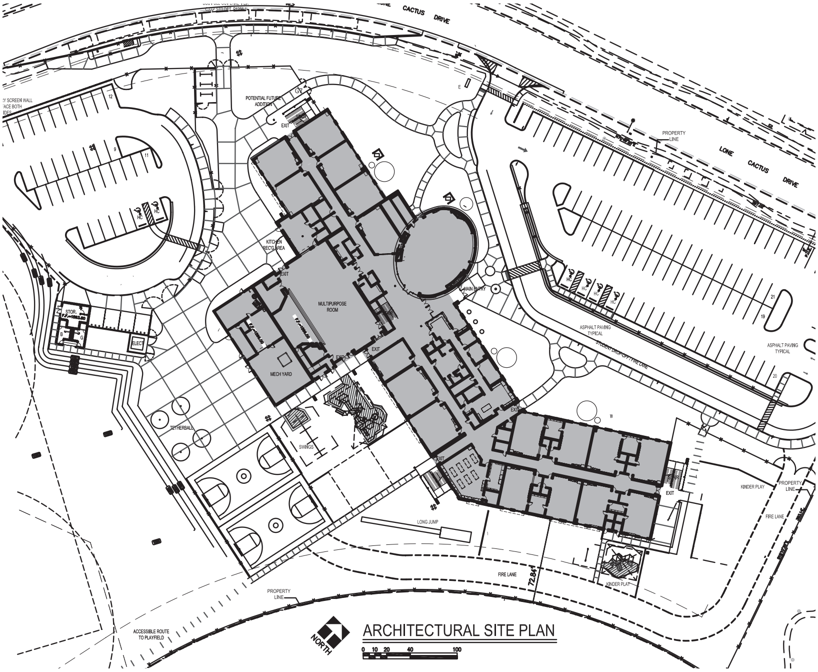


Figure 8.20 Fireside Elementary site plan © 2016 DLR Group.

Building Summary

Project location: Phoenix, AZ
Architect: DLR Group
Project type: elementary school
Project size: 86,650 ft^2 (8,050 m^2)

Envelope Metrics

Dimensions above grade: 457' × 266' × 32'
Exterior wall area/floor area: 0.37
Floor area/(exterior wall area + roof area): 1.074
Window–wall ratio: 0.091
Average exterior U-value (UA):

- Wall = 0.113 Btu/h/ft^2/°F
- Roof = 0.260 Btu/h/ft^2/°F

Simulated EUI: 4.76 kBtu/ft^2/yr
Actual EUI: 9.78 kBtu/ft^2/yr

Project Description[13]

A growing environmental concern, shrinking operational budget, and demand for technology propelled Paradise Valley Unified School District to embrace energy efficiency when planning Fireside Elementary School. DLR Group designers—who provided architecture, engineering, and interior design services—partnered with the district to adopt a net-zero design approach from the very beginning to achieve near net-zero operations, making this a showcase school and the most efficient in the district upon opening. The two-story, 86,650 ft^2 elementary school serves 880 students in kindergarten through Grade 6, and the building serves as a teaching tool to illustrate water conservation and solar energy production techniques. Rainwater collection silos are prominent at the front of this school so that students and community members can observe firsthand the commitment to sustainable rainwater harvesting practices. Cisterns collect rainwater for landscape and playfield irrigation, and TV screens in the lobby display and monitor energy use and production from the school's photovoltaic system, allowing students to see how their building impacts the environment. The design challenge was near net-zero for typical construction costs. It incorporates high thermal mass walls to take advantage of diurnal temperature differences; daylighting with controls; HVAC system for effective maintenance and efficient operation; and renewable-energy systems. The design solution is a high-performance design that provides a twenty-first-century learning environment with daylighting in every teaching space, and meets the net-zero energy goal with just Phase-I of the renewable-energy system.

Hawaii Preparatory Academy Energy Lab

Figure 8.21 **Hawaii Preparatory Academy Energy Lab photograph © Matt Millman Photography.**

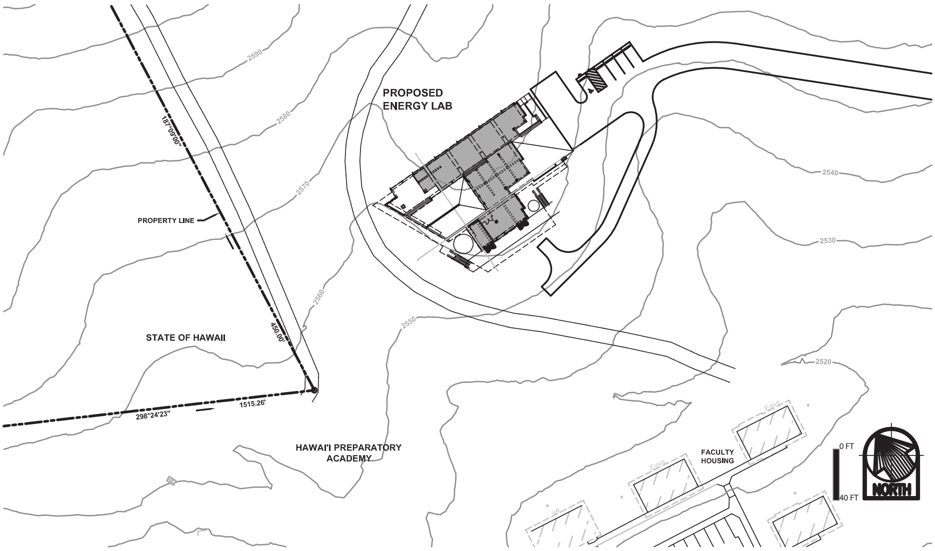


Figure 8.22 **Hawaii Preparatory Academy site plan © Flansburg Architects.**

Building Summary

Project location: New Science Building, Kamuela, HI
Architect: Flansburg Architects
Sustainability consultants: Buro Happold
Project type: educational
Project size: 6,100 ft^2 (567 m^2)

Envelope Metrics

Dimensions above grade: 105' × 80' × 20'
Exterior wall area/floor area: (7,005/6,100) = 1.148
Floor area/(exterior wall area + roof area): (6,100/12,978) = 0.47
Window–wall ratio: 0.40
Average exterior U-value (UA):

- Wall = 0.09 Btu/h/ft^2/°F; roof = 0.044 Btu/h/ft^2/°F

Simulated EUI: 5.36 kWh/ft^2/yr
Actual EUI: 3.23 kWh/ft^2/yr

Project Description

In this new 6,100 ft^2 renewable-energy research laboratory, students will study, design, and evaluate renewable-energy technologies. The award-winning facility meets the Living Building Challenge, a threshold that exceeds the USGBC's Platinum LEED rating. It produces power for all of its own energy needs, harvests rainwater to meet its potable water needs, and provides natural ventilation and views to 100 percent of its occupied spaces. Sophisticated energy models were used to form the shape and fenestration of the building during the design. The project is the recipient of multiple honors and awards, including the Buckminster Fuller Challenge and AIA Honolulu Award of Excellence.[14]

Further reading

The following sources are where to find information about high-performing and sustainably designed building projects.

Energy Star National Building Competition (Environmental Protection Agency and the Department of Energy), www.energystar.gov/buildings/tools-and-resources/energy-star-national-building-competition-2013-summary.

Building Catalog: Case Studies of High Performance Buildings (Department of Energy, 2016), https://buildingdata.energy.gov.

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2030 Palette (Architecture 2030), http://2030palette.org.

Notes

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2 Reprinted with permission from the Miller Hull Partnership LLP, *Bullitt Center*, www.millerhull.com/html/nonresidential/bullitt.htm.
3 Reprinted with permission from Leo A. Daly, *SAC Federal Credit Union Headquarters*, www.leoadaly.com/portfolio/sac-federal-credit-union.
4 Reprinted with permission from Studio Twenty Seven Architecture, *La Casa Permanent Supportive Housing*, www.studio27arch.com/project/la-casa-permanent-supportive-housing.
5 For more information, visit the Department of General Services, www.dgs.dc.gov/lacasa_project.
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8 Studio Twenty Seven Architecture, *Fragment 07 La Casa Permanent Supportive Housing, 2015*, http://issuu.com/studio27arch/docs/fragment_07_la_casa_permanent_suppo/1. Page 2.
9 Reprinted with permission from Perkins + Will, *Durham County Human Services Building*, http://perkinswill.com/work/durham-county-human-services-building.
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14 Reprinted with permission from Flansburgh Architects, *Hawaii Preparatory Academy Energy Lab*, www.flansburgh.com/portfolio/hawaii-preparatory-academy-energy-lab.

Appendices

A.1: Comparison of Various BEM Tools

BEM Tool	*Calculation engine*	*GUI*	*Graphic results*	*Early design*	*Code compliance*	*Users*	*Interoperability*	*URL*
COMFEN	E+	Y	Y	Y	N	A,E	N	1
Daysim	External; radiance	N	N	Y	N	A,E	Y	2
DesignBuilder	External; E+, radiance, jE+	Y	Limited	Y	Y	E	Y	3
DOE2	Standalone	N	N	N	Y	E	N	4
DIVA for Rhino	Plug-in; radiance	Y	N	Y	N	A,E	N	5
EMIT1.2	Spreadsheet	N	N	Y	N	A,E	N	6
EnergyPlus (E+)	Standalone	N	N	N	Y	E	N	7
EnergyPro	External; DOE2	N	N	N	Y	A,E	N	8
eQUEST	External; DOE2	Y	N	N	Y	E	N	9
Green Building Studio	Plug-in; DOE2	Y	Y	Y	N	A,E	Y	10
Ladybug/HoneyBee for Rhino	Plug-in; OpenStudio, E+, Radiance	N	Y	Y	N	A,E	Y	11
Hourly Analysis Program (HAP)	Standalone	N	N	N	Y	E	N	12
IES Virtual Environment	Standalone	Y	Y	Y	Y	A,E	Y	13
jEPlus	Plug-in; E+, DesignBuilder, Transys	N	N	Y	N	E	R	14

(Continued)

A.1: Comparison of Various BEM Tools (*Continued*)

BEM Tool	*Calculation engine*	*GUI*	*Graphic results*	*Early design*	*Code compliance*	*Users*	*Interoperability*	*URL*
N++	External; E+, GeNpt	Y	Y	Y	N	E	Y	15
OpenStudio	External; E+, Radiance	Y	Y	N	Y	E	Y	16
Parametric Analysis Tool	Plug-in; OpenStudio	Y	Y	N	Y	E	Y	17
Radiance	Standalone	N	Y	Y	N	A, E	N	18
Sefaira	External; E+, Radiance	Y	Y	Y	N	A, E	R	19
Solon	Plug-in; GBS	Y	Y	Y	N	A, E	Y	
Simergy	External; E+	Y	Y	N	Y	E	Y	20
TAS	Standalone	Y	Y	Y	Y	E	N	21
TRACE 700	Standalone	N	Limited	N	Y	E	Y	22
TRNSYS	Standalone	Y	N	N	N	E	N	23

Notes:

See Chapter 4 for discussion on the relationship between the BEM tool and simulation engines, noted as standalone, external, and plug-in.

R = runtime; Y = yes; N = no; A = Architect; E = Engineer.

Sources: Shady Attia, Elisabeth Gratia, André de Herde, and Jan L.M. Hensen, "Simulation-Based Decision Support Tool for Early Stages of Zero-Energy Building Design," *Energy and Buildings* 49 (2012): 2–15. doi:10.1016/j.enbuild.2012.01.028; Torben Østergård, Rasmus L. Jensen, and Steffen E. Maagaard, "Building Simulations Supporting Decision Making in Early Design: A Review," *Renewable and Sustainable Energy Reviews* 61 (2016): 187–201. doi:10.1016/j.rser.2016.03.045; International Building Performance Simulation Association-USA, "BEST Directory," www.buildingenergysoftwaretools.com; Reprinted with permissions from the Energy Modeling Working Group, *AIA Guide to Integrating Energy Modeling in the Design Process* (Washington, DC: AIA, 2013), 56; Thomas Reeves, Svetlana Olbina, and Raja R.A. Issa, "Guidelines for Using Building Information Modeling for Energy Analysis of Buildings," *Buildings* 5, no. 4 (2015): 1361–1388; Drury B. Crawley, Jon W. Hand, Michaël Kummert, and Brent T. Griffith, "Contrasting the Capabilities of Building Energy Performance Simulation Programs," *Building and Environment* 43, no. 4 (2008): 661–673.

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4 Jeff Hirsch, "DOE2.com," http://doe2.com/doe2.
5 Kera Lagios, "DIVE for Rhino," http://diva4rhino.com.
6 Rocky Mountain Institute, "Modeling Tools," www.rmi.org/ModelingTools.
7 National Renewable Energy Laboratory, "EnergyPlus," https://energyplus.net.
8 EnergySoft, "Energy Pro Version 7.0," www.energysoft.com.
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11 Mostapha S. Roudasri, "Ladybug + Honeybee," www.food4rhino.com/project/ladybug-honeybee?ufh.
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16 National Renewable Energy Laboratory, "OpenStudio" www.openstudio.net.
17 National Renewable Energy Laboratory, "Parametric Analysis Tool (PAT) Interface Guide," http://nrel.github.io/OpenStudio-user-documentation/reference/parametric_studies.
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20 Digital Alchemy, "Simergy," www.digitalalchemypro.com/html/products/DAProducts_Simergy.html.
21 EDSL, "TAS Software," www.edsl.net/main/Software.aspx.
22 Trane, "Trace 700," www.trane.com/commercial/north-america/us/en/products-systems/design-and-analysis-tools/analysis-tools/trace-700.html.
23 Mechanical Engineering Department, Board of Regents of the University of Wisconsin System, "TRNSYS17," http://sel.me.wisc.edu/trnsys/features.

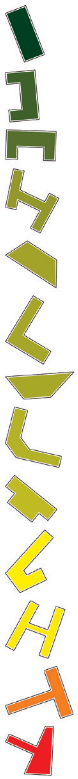
A.2: All Shape Simulation Outcomes Presented in the Pattern Guide

Small

Miami	*General info*	*EUI*	*CUI*	*Lighting (sDA Based)*	*Lighting (reduced LPD)*	*Lighting + Dim/Sched)*	*sDA*	*ASE*	*Total lux deficiency (from 300/point)*	*Carbon from lighting /area (lighting CUI)*
1	Ori:120, Edges (Window/Level):12,	107.44	9.58	1,402.55	3,431.46	3,309.85	92.37	31.06	19,565,739.00	1.60
2	Ori:169, Edges (Window/Level):8,	108.06	10.48	2,172.81	4,298.40	8,292.67	84.13	24.87	31,347,975.00	2.91
3	Ori:11, Edges (Window/Level):4,	108.38	9.86	3,203.55	6,134.61	5,187.79	66.67	11.46	44,764,857.00	2.86
4	Ori:37, Edges (Window/Level):12,	108.75	9.66	1,658.93	3,911.61	3,230.59	87.80	30.62	23,169,524.00	1.73
5	Ori:17, Edges (Window/Level):6,	112.73	10.77	2,873.79	5,160.30	8,336.98	75.93	17.77	39,525,098.00	3.22
6	Ori:156, Edges (Window/Level):6,	112.74	10.53	3,076.48	5,173.43	7,493.29	75.81	20.70	42,432,173.00	3.10
7	Ori:161, Edges (Window/Level):4,	112.79	10.38	3,640.49	6,125.71	6,888.60	66.75	10.41	52,356,922.00	3.28
8	Ori:68, Edges (Window/Level):8,	113.50	9.83	3,621.39	6,072.80	3,810.44	67.25	15.37	51,494,909.00	2.66
9	Ori:63, Edges (Window/Level):8,	115.62	10.57	2,672.24	4,212.24	6,673.67	84.95	36.56	37,857,123.00	2.67
10	Ori:22, Edges (Window/Level):4,	121.60	11.00	5,148.45	7,335.24	8,153.12	64.14	19.70	75,660,362.00	4.06
11	Ori:178, Edges (Window/Level):4,	121.81	10.93	4,864.00	6,819.69	7,651.82	60.15	9.64	69,953,339.00	3.81
12	Ori:83, Edges (Window/Level):6,	122.62	11.44	3,780.08	4,798.31	9,718.51	79.37	40.99	52,695,708.00	3.60
13	Ori:168, Edges (Window/Level):8,	126.64	11.17	5,145.06	6,400.18	7,808.38	84.92	25.13	31,034,522.00	3.81

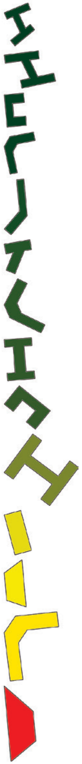
New York	General info	EUI	CUI	Lighting (sDA Based)	Lighting (reduced LPD)	Lighting + Dim/Sched)	sDA	ASE	Total lux deficiency (from 300/point)	Carbon from lighting /area (lighting CUI)
1	Ori:98, Edges (Window/Level):8,	164.55	16.21	4,470.73	4,520.97	7,683.67	82.01	38.89	64,500,952.00	4.02
2	Ori:65, Edges (Window/Level):12,	164.69	15.89	3,417.64	3,431.46	3,761.53	92.37	46.87	47,676,371.00	3.07
3	Ori:4, Edges (Window/Level):8,	165.38	16.24	4,347.95	4,657.09	6,607.87	80.72	37.74	60,841,694.00	3.91
4	Ori:69, Edges (Window/Level):4,	166.30	16.77	5,709.73	6,654.95	6,002.93	61.72	25.52	79,785,056.00	5.13
5	Ori:153, Edges (Window/Level):8,	166.98	16.47	4,708.09	5,196.13	8,182.38	75.59	27.30	66,990,524.00	4.23
6	Ori:169, Edges (Window/Level):6,	167.47	16.72	5,331.10	5,484.40	7,259.51	72.85	33.06	73,528,793.00	4.79
7	Ori:185, Edges (Window/Level):4,	168.71	17.06	6,102.75	6,499.39	8,183.30	63.20	21.83	87,768,772.00	5.48
8	Ori:118, Edges (Window/Level):8,	169.92	17.15	6,020.62	6,496.64	4,651.71	63.22	23.68	85,611,106.00	5.41
9	Ori:168, Edges (Window/Level):8,	170.59	17.09	5,629.43	5,669.69	6,368.95	71.09	27.59	78,228,209.00	5.06
10	Ori:166, Edges (Window/Level):8,	173.24	17.36	5,739.72	5,908.74	7,792.54	68.81	41.24	80,970,012.00	5.16
11	Ori:185, Edges (Window/Level):4,	175.68	17.94	7,008.77	6,926.46	8,529.33	59.14	23.35	100,799,103.00	6.30
12	Ori:146, Edges (Window/Level):6,	176.02	17.62	5,822.21	4,880.69	9,205.97	78.59	38.12	81,163,830.00	5.23
13	Ori:185, Edges (Window/Level):4,	177.07	18.27	7,599.20	7,939.94	8,606.30	49.50	21.25	107,972,270.00	6.83

Omaha	*General info*	*EUI*	*CUI*	*Lighting (sDA Based)*	*Lighting (reduced LPD)*	*Lighting + Dim/Sched)*	*sDA*	*ASE*	*Total lux deficiency (from 300/point)*	*Carbon from lighting /area (lighting CUI)*
1	Ori:19, Edges (Window/Level):4,	207.33	26.50	4,547.99	6,408.47	6,805.11	64.06	17.19	63,551,398.00	7.24
2	Ori:65, Edges (Window/Level):12,	210.27	25.21	2,625.99	3,883.11	4,400.08	88.08	42.82	36,675,995.00	4.18
3	Ori:38, Edges (Window/Level):6,	210.61	25.99	3,442.73	4,611.73	10,221.32	81.15	30.05	49,350,298.00	5.48
4	Ori:4, Edges (Window/Level):6,	211.01	26.44	4,063.68	5,682.29	10,097.36	70.97	27.42	56,048,058.00	6.46
5	Ori:7, Edges (Window/Level):12,	211.16	25.15	2,342.47	3,660.71	4,277.12	90.19	47.68	32,677,660.00	3.73
6	Ori:167, Edges (Window/Level):4,	211.17	27.02	4,801.37	6,365.93	7,518.04	64.47	20.30	69,052,605.00	7.64
7	Ori:38, Edges (Window/Level):12,	211.42	25.70	3,015.20	4,703.60	0.00	80.27	33.70	42,504,505.00	4.80
8	Ori:164, Edges (Window/Level):8,	211.95	25.89	3,216.69	4,541.20	7,858.76	81.82	31.96	45,011,691.00	5.12
9	Ori:127, Edges (Window/Level):4,	212.28	27.33	4,898.42	6,582.48	9,498.74	62.41	20.64	70,877,147.00	7.79
10	Ori:141, Edges (Window/Level):8,	214.37	27.46	4,822.61	6,549.62	4,697.90	62.72	27.71	68,575,743.00	7.67
11	Ori:41, Edges (Window/Level):12,	219.54	27.60	4,406.96	5,204.58	7,248.34	87.53	42.55	36,272,431.00	7.01
12	Ori:137, Edges (Window/Level):4,	220.04	28.56	5,536.04	6,873.07	8,861.57	59.64	26.14	79,618,547.00	8.81
13	Ori:2, Edges (Window/Level):8,	221.23	29.43	6,432.03	7,755.90	9,866.76	75.51	35.20	62,472,034.00	10.23

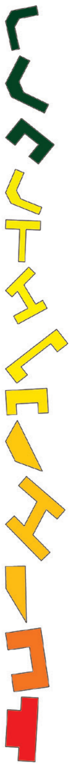


Phoenix	General info	EUI	CUI	Lighting (sDA Based)	Lighting (reduced LPD)	Lighting + Dim/Sched)	sDA	ASE	Total lux deficiency (from 300/point)	Carbon from lighting /area (lighting CUI)
1	Ori:21, Edges (Window/Level):4,	131.58	12.04	3,282.78	5,942.90	6,132.45	68.49	26.82	45,871,937.00	2.13
2	Ori:5, Edges (Window/Level):8,	134.03	12.25	2,650.31	5,157.67	6,956.66	75.96	37.16	36,600,579.00	1.72
3	Ori:44, Edges (Window/Level):12,	134.51	12.30	2,616.90	4,899.07	5,569.19	88.89	46.61	22,894,676.00	1.70
4	Ori:166, Edges (Window/Level):8,	135.61	12.37	1,639.25	3,797.61	3,190.70	82.13	42.93	33,777,514.00	1.07
5	Ori:141, Edges (Window/Level):8,	135.88	12.46	3,588.86	6,298.26	7,964.74	65.99	30.48	47,873,725.00	2.33
6	Ori:57, Edges (Window/Level):4,	135.94	12.42	2,432.49	4,468.06	8,571.10	65.11	35.63	51,928,534.00	1.58
7	Ori:94, Edges (Window/Level):4,	135.96	12.45	3,064.09	5,645.26	6,450.64	71.32	40.61	44,067,288.00	1.99
8	Ori:96, Edges (Window/Level):4,	136.20	12.46	2,414.02	4,508.06	4,742.43	65.85	30.71	49,054,981.00	1.57
9	Ori:88, Edges (Window/Level):8,	136.42	12.50	3,366.73	6,205.25	3,223.77	78.42	42.90	36,139,176.00	2.19
10	Ori:138, Edges (Window/Level):8,	138.90	12.68	2,551.22	4,864.90	7,048.80	78.74	40.16	36,300,898.00	1.66
11	Ori:82, Edges (Window/Level):12,	139.23	12.67	1,108.88	2,777.66	2,394.79	98.59	47.74	15,728,415.00	0.72
12	Ori:109, Edges (Window/Level):8,	142.36	13.02	2,677.36	4,325.32	4,676.42	83.87	46.24	37,929,583.00	1.74
13	Ori:66, Edges (Window/Level):8,	145.24	13.32	3,831.82	5,854.53	6,385.92	69.33	37.11	54,055,414.00	2.49

Medium



Miami	General Info	EUI	CUI	Lighting (sDA Based)	Lighting (reduced LPD)	Lighting (+Dim/Sched)	sDA	ASE	Total lux deficiency (from 300/point)	Carbon from lighting /area (lighting CUI)
1	FLR:3.0, Ori:185, Edges (Window/Level):12,	123.79	10.16	25,351.79	43,032.14	74,992.23	84.08	27.56	245,586,320.00	1.50
2	FLR:2.0, Ori:43, Edges (Window/Level):12,	125.53	10.31	37,185.60	50,996.77	88,808.39	76.51	27.81	355,513,029.00	2.20
3	FLR:3.0, Ori:185, Edges (Window/Level):8,	126.01	10.35	34,123.92	50,548.58	129,157.79	76.93	21.94	335,672,149.00	2.01
4	FLR:3.0, Ori:185, Edges (Window/Level):6,	132.75	10.90	45,944.41	48,492.61	127,119.73	78.89	20.21	447,027,349.00	2.71
5	FLR:3.0, Ori:10, Edges (Window/Level):8,	134.86	11.08	49,722.14	57,375.57	96,507.45	70.44	20.14	486,972,063.00	2.94
6	FLR:2.0, Ori:153, Edges (Window/Level):8,	135.61	11.14	57,042.46	64,287.58	118,409.79	63.87	18.52	548,862,422.00	3.37
7	FLR:2.0, Ori:185, Edges (Window/Level):12,	135.99	11.17	55,805.94	61,813.96	114,255.50	66.22	21.59	540,819,689.00	3.29
8	FLR:2.0, Ori:51, Edges (Window/Level):8,	136.40	11.20	58,432.87	65,355.55	130,873.95	62.85	17.07	561,000,763.00	3.45
9	FLR:1.0, Ori:54, Edges (Window/Level):12,	144.27	11.84	81,098.72	75,135.62	126,756.85	53.55	17.84	774,194,297.00	4.79
10	FLR:2.0, Ori:15, Edges (Window/Level):4,	155.55	12.79	92,523.32	89,971.86	119,330.37	39.45	10.79	889,803,382.00	5.46
11	FLR:2.0, Ori:185, Edges (Window/Level):4,	158.55	13.04	96,482.60	88,206.64	135,446.72	41.13	12.46	934,274,742.00	5.70
12	FLR:1.0, Ori:96, Edges (Window/Level):8,	169.23	13.91	120,104.80	94,997.38	135,987.28	34.67	11.75	1,154,512,606.00	7.09
13	FLR:1.0, Ori:185, Edges (Window/Level):4,	201.62	16.58	170,035.21	103,863.84	149,243.23	26.24	7.29	1,652,048,732.00	10.04



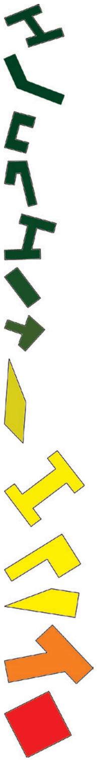
New York	General Info	EUI	CUI	Lighting (sDA Based)	Lighting (reduced LPD)	Lighting (+Dim/Sched)	sDA	ASE	Total lux deficiency (from 300/point)	Carbon from lighting /area (lighting CUI)
1	FLR:3.0, Ori:101, Edges (Window/Level):8,	126.41	11.52	34,496.83	51,153.59	101,665.94	76.36	22.60	334,618,965.00	3.10
2	FLR:2.0, Ori:153, Edges (Window/Level):8,	133.99	12.90	57,042.46	64,287.58	118,409.79	63.87	18.52	548,862,422.00	5.12
3	FLR:2.0, Ori:51, Edges (Window/Level):8,	134.73	13.00	58,432.87	65,355.55	130,873.95	62.85	17.07	561,000,763.00	5.25
4	FLR:3.0, Ori:157, Edges (Window/Level):8,	184.80	18.33	58,246.78	53,701.71	101,834.00	73.94	34.03	564,993,284.00	5.23
5	FLR:3.0, Ori:178, Edges (Window/Level):8,	185.23	18.25	55,148.27	49,557.71	110,757.15	77.88	35.40	532,686,904.00	4.95
6	FLR:2.0, Ori:11, Edges (Window/Level):12,	189.02	18.88	67,618.63	56,779.50	109,496.27	71.01	26.50	653,170,439.00	6.07
7	FLR:2.0, Ori:128, Edges (Window/Level):8,	198.76	20.21	82,758.08	67,849.37	122,388.92	60.48	22.90	814,981,339.00	7.43
8	FLR:2.0, Ori:93, Edges (Window/Level):8,	203.25	20.98	95,481.23	79,049.75	136,684.19	49.83	26.21	936,892,134.00	8.58
9	FLR:2.0, Ori:26, Edges (Window/Level):4,	211.13	22.17	111,660.62	86,395.39	134,014.44	42.85	15.65	1084,885,824.00	10.03
10	FLR:1.0, Ori:170, Edges (Window/Level):12,	213.28	22.20	112,431.65	87,014.63	123,937.01	42.26	19.64	1080,422,787.00	10.10
11	FLR:2.0, Ori:1, Edges (Window/Level):4,	214.56	22.60	116,105.61	83,828.75	146,425.07	45.29	19.46	1128,072,949.00	10.43
12	FLR:1.0, Ori:8, Edges (Window/Level):8,	231.17	24.65	142,021.17	97,952.08	143,485.24	31.86	17.84	1361,650,492.00	12.76
13	FLR:1.0, Ori:87, Edges (Window/Level):8,	256.43	28.06	182,144.36	105,147.52	139,614.82	25.02	13.44	1762,088,219.00	16.36

Omaha	General Info	EUI	CUI	Lighting (sDA Based)	Lighting (reduced LPD)	Lighting (+Dim/Sched)	sDA	ASE	Total lux deficiency (from 300/point)	Carbon from lighting /area (lighting CUI)
1	FLR:2.0, Ori:153, Edges (Window/Level):8,	140.84	16.85	57,042.46	64,287.58	118,409.79	63.87	18.52	548,862,422.00	9.07
2	FLR:2.0, Ori:51, Edges (Window/Level):8,	141.75	17.05	58,432.87	65,355.55	130,873.95	62.85	17.07	561,000,763.00	9.30
3	FLR:3.0, Ori:157, Edges (Window/Level):12,	233.30	28.41	37,248.45	45,316.70	84,151.58	81.91	35.29	360,830,888.00	5.93
4	FLR:2.0, Ori:20, Edges (Window/Level):8,	247.67	32.23	70,370.87	64,259.26	126,092.55	63.90	24.86	692,995,050.00	11.20
5	FLR:3.0, Ori:340, Edges (Window/Level):4,	249.03	32.86	74,651.77	72,057.30	140,261.14	56.48	21.19	735,680,939.00	11.88
6	FLR:3.0, Ori:71, Edges (Window/Level):8,	249.44	32.02	65,496.63	64,232.95	121,138.08	63.92	31.55	623,672,555.00	10.42
7	FLR:1.0, Ori:128, Edges (Window/Level):12,	253.19	33.28	82,218.24	73,860.53	118,292.74	54.77	20.20	783,293,022.00	13.08
8	FLR:3.0, Ori:41, Edges (Window/Level):4,	255.00	34.50	86,843.84	81,372.24	129,519.00	47.62	17.07	832,888,457.00	13.82
9	FLR:2.0, Ori:345, Edges (Window/Level):8,	260.15	35.16	91,483.99	76,924.72	129,888.56	51.85	21.43	885,800,334.00	14.55
10	FLR:1.0, Ori:137, Edges (Window/Level):12,	261.49	35.05	93,458.02	78,478.17	129,401.94	50.38	20.40	892,180,097.00	14.87
11	FLR:2.0, Ori:63, Edges (Window/Level):4,	265.75	36.79	104,349.16	93,814.97	137,029.09	35.79	18.99	1003,533,391.00	16.60
12	FLR:2.0, Ori:0, Edges (Window/Level):4,	269.95	37.62	110,782.50	88,911.02	143,837.67	40.46	14.74	1072,745,660.00	17.62
13	FLR:1.0, Ori:8, Edges (Window/Level):12,	284.37	39.89	125,986.43	92,534.72	132,036.16	37.01	16.90	1205,954,480.00	20.04

Phoenix	General Info	EUI	CUI	Lighting (sDA Based)	Lighting (reduced LPD)	Lighting (+Dim/Sched)	sDA	ASE	Total lux deficiency (from 300/point)	Carbon from lighting /area (lighting CUI)
1	FLR:3.0, Ori:101, Edges (Window/Level):8,	126.24	10.67	34,496.83	51,153.59	101,665.94	76.36	22.60	334,618,965.00	2.24
2	FLR:3.0, Ori:49, Edges (Window/Level):8,	130.48	11.88	11,008.51	26,474.90	18,635.60	99.83	58.84	106,550,328.00	0.72
3	FLR:2.0, Ori:153, Edges (Window/Level):8,	133.72	11.48	57,042.46	64,287.58	118,409.79	63.87	18.52	548,862,422.00	3.71
4	FLR:2.0, Ori:174, Edges (Window/Level):8,	134.91	12.32	22,946.42	38,245.10	92,703.49	88.63	50.57	220,303,379.00	1.49
5	FLR:2.0, Ori:54, Edges (Window/Level):8,	135.95	12.42	23,264.05	41,149.79	70,536.09	85.87	48.51	223,352,891.00	1.51
6	FLR:3.0, Ori:128, Edges (Window/Level):8,	136.27	12.44	11,113.79	27,346.83	34,898.68	99.00	69.85	107,803,632.00	0.72
7	FLR:3.0, Ori:127, Edges (Window/Level):6,	139.85	12.75	13,842.96	32,024.11	40,782.09	94.55	69.31	134,688,513.00	0.90
8	FLR:3.0, Ori:146, Edges (Window/Level):12,	140.73	12.84	8,988.56	26,366.08	175,72.04	99.93	78.31	87,073,461.00	0.58
9	FLR:3.0, Ori:110, Edges (Window/Level):12,	142.84	13.01	8,381.79	26,291.18	18,234.68	100.00	72.96	81,013,820.00	0.54
10	FLR:2.0, Ori:8, Edges (Window/Level):4,	176.37	16.30	93,632.88	91,193.03	122,508.49	38.29	16.73	900,474,101.00	6.09
11	FLR:1.0, Ori:164, Edges (Window/Level):12,	178.15	16.38	95,874.73	87,698.91	121,757.23	41.61	25.03	919,077,804.00	6.23
12	FLR:1.0, Ori:116, Edges (Window/Level):8,	185.42	17.08	107,749.43	84,416.19	139,266.98	44.73	20.98	1,024,349,435.00	7.00
13	FLR:1.0, Ori:8, Edges (Window/Level):4,	226.95	21.05	178,080.20	107,888.61	147,959.36	22.41	10.91	1,726,889,913.00	11.57

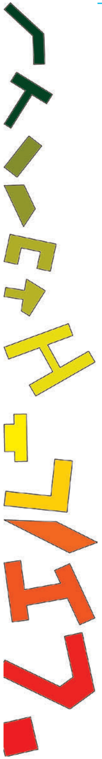
Large

Miami	General Info	EUI	CUI	Lighting(sDA Based)	Lighting (Reduced LPD)	Lighting(+Dim/ Sched)	sDA	ASE	Total Lux Deficiency (from 300/point)	Carbon from Lighting /Area (lighting CUI)
1	FLR:12.0, Ori:246, Edges (Window/Level):8,	143.88	11.81	49,4267.96	641,758.11	926,537.38	63.98	19.76	1,902,956,028.00	2.92
2	FLR:11.0, Ori:85, Edges (Window/Level):8,	144.49	11.86	53,0938.81	653,718.87	1,062,900.00	62.84	19.07	2,040,766,266.00	3.13
3	FLR:8.0, Ori:126, Edges (Window/Level):12,	144.56	11.87	54,4198.86	720,002.96	1,066,700.00	56.54	15.00	2,071,773,640.00	3.21
4	FLR:12.0, Ori:94, Edges (Window/Level):6,	146.96	12.07	53,3967.28	606,670.52	1,279,200.00	67.31	20.58	2,044,568,508.00	3.15
5	FLR:12.0, Ori:170, Edges (Window/Level):8,	160.43	13.18	79,0414.54	867,788.52	723,483.97	42.48	15.95	3,051,980,568.00	4.67
6	FLR:7.0, Ori:0, Edges (Window/Level):8,	162.66	13.37	85,2859.89	767,846.40	1,363,200.00	51.99	11.78	3,268,289,339.00	5.04
7	FLR:9.0, Ori:337, Edges (Window/Level):8,	164.36	13.51	86,8948.78	848,650.57	1,325,500.00	44.30	12.07	3,392,085,681.00	5.13
8	FLR:4.0, Ori:88, Edges (Window/Level):12,	171.34	14.08	1,042,800.00	906,940.64	1,433,200.00	38.76	12.17	3,958,889,232.00	6.16
9	FLR:6.0, Ori:234, Edges (Window/Level):6,	171.41	14.09	1,035,000.00	958,720.01	1,482,600.00	33.84	9.75	3,942,893,652.00	6.11
10	FLR:10.0, Ori:303, Edges (Window/Level):4,	174.25	14.32	996,903.08	866,818.14	1,404,100.00	42.58	12.88	3,920,357,810.00	5.89
11	FLR:5.0, Ori:183, Edges (Window/Level):6,	190.93	15.70	1,351,900.00	1,022,400.00	1,379,700.00	27.78	7.52	5,161,231,610.00	7.98
12	FLR:3.0, Ori:233, Edges (Window/Level):8,	197.56	16.25	1,469,700.00	1,036,400.00	1,510,200.00	26.45	8.91	5,528,816,787.00	8.68
13	FLR:3.0, Ori:111, Edges (Window/Level):4,	241.83	19.91	2,144,000.00	1,158,300.00	1,511,400.00	14.86	4.06	8,243,857,554.00	12.66



New York	General Info	EUI	CUI	Lighting(sDA Based)	Lighting (Reduced LPD)	Lighting(+Dim/ Sched)	sDA	ASE	Total Lux Deficiency (from 300/point)	Carbon from Lighting /Area (lighting CUI)
1	FLR:9.0, Ori:233, Edges (Window/Level):12,	211.52	20.83	75,4003.26	704,584.96	98,0271.12	58.00	23.87	2,881,193,175.00	6.77
2	FLR:10.0, Ori:69, Edges (Window/Level):6,	213.09	21.17	821,256.14	661,342.35	1,385,300.00	62.11	22.13	3,117,839,380.00	7.38
3	FLR:12.0, Ori:165, Edges (Window/Level):8,	214.85	21.29	817,874.35	839,830.11	1,294,500.00	45.14	19.31	3,105,705,732.00	7.35
4	FLR:11.0, Ori:13, Edges (Window/Level):8,	216.03	21.53	856,820.90	779,174.90	1,199,400.00	50.91	21.28	3,297,642,293.00	7.70
5	FLR:8.0, Ori:147, Edges (Window/Level):12,	218.09	21.79	887,691.55	791,188.61	1,200,400.00	49.77	22.86	3,380,558,264.00	7.97
6	FLR:12.0, Ori:217, Edges (Window/Level):4,	222.37	22.58	1,003,900.00	967,739.08	999,556.38	32.98	15.01	3,812,388,780.00	9.02
7	FLR:12.0, Ori:71, Edges (Window/Level):8,	225.96	22.90	1,013,300.00	819,388.73	1,230,500.00	47.09	18.95	3,947,644,944.00	9.10
8	FLR:7.0, Ori:176, Edges (Window/Level):4,	244.22	25.55	1,367,200.00	913,627.28	1,471,100.00	38.12	13.97	5,183,241,560.00	12.28
9	FLR:4.0, Ori:308, Edges (Window/Level):12,	251.10	26.48	1,490,900.00	1,030,300.00	1,428,300.00	27.03	12.46	5,628,767,668.00	13.39
10	FLR:5.0, Ori:302, Edges (Window/Level):6,	252.52	26.67	1,510,400.00	1,054,800.00	1,448,700.00	24.70	11.03	5,766,508,245.00	13.57
11	FLR:6.0, Ori:261, Edges (Window/Level):4,	256.20	27.17	1,551,200.00	1,013,900.00	1,497,400.00	28.59	16.84	6,023,362,284.00	13.93
12	FLR:3.0, Ori:313, Edges (Window/Level):8,	278.37	30.17	1,939,400.00	1,120,000.00	1,502,800.00	18.50	9.95	7,389,895,281.00	17.42
13	FLR:3.0, Ori:297, Edges (Window/Level):4,	296.35	32.64	2,234,800.00	1,171,600.00	1,513,200.00	13.60	5.21	8,592,475,554.00	20.07

Omaha	General Info	EUI	CUI	Lighting(sDA Based)	Lighting (Reduced LPD)	Lighting(+Dim/ Sched)	sDA	ASE	Total Lux Deficiency (from 300/point)	Carbon from Lighting /Area (lighting CUI)
1	FLR:12.0, Ori:208, Edges (Window/Level):12,	261.81	31.73	507,864.05	597,701.02	916,077.49	68.17	26.25	1930,705,788.00	8.08
2	FLR:10.0, Ori:198, Edges (Window/Level):8,	268.77	33.82	686,032.96	739,572.98	1,255,000.00	54.67	19.82	2611,140,540.00	10.91
3	FLR:7.0, Ori:146, Edges (Window/Level):13,	275.25	34.92	748,770.58	801,418.88	1,223,400.00	48.79	23.16	2852,899,140.00	11.91
4	FLR:9.0, Ori:324, Edges (Window/Level):8,	279.78	36.42	874,793.72	840,760.26	1,374,500.00	45.05	17.05	3373,590,933.00	13.92
5	FLR:11.0, Ori:239, Edges (Window/Level):4,	290.89	38.86	1,018,000.00	872,118.34	1,355,900.00	42.07	22.87	387,789,8937.00	16.20
6	FLR:10.0, Ori:329, Edges (Window/Level):8,	292.44	39.27	1,073,500.00	969,105.01	1,007,600.00	32.85	15.50	410,881,7580.00	17.08
7	FLR:8.0, Ori:338, Edges (Window/Level):6,	292.56	39.34	1,089,000.00	910,141.02	1,401,000.00	38.46	13.53	4,194,966,416.00	17.33
8	FLR:12.0, Ori:111, Edges (Window/Level):4,	293.18	39.65	1,1030,00.00	985,042.78	1,242,100.00	31.33	14.44	4,376,572,632.00	17.55
9	FLR:4.0, Ori:242, Edges (Window/Level):6,	317.18	44.47	1,455,800.00	1,041,200.00	1,489,600.00	26.00	12.38	5,506,242,424.00	23.16
10	FLR:6.0, Ori:116, Edges (Window/Level):4,	324.49	46.27	1,560,100.00	1,083,200.00	1,379,700.00	22.00	9.01	6,048,478,176.00	24.82
11	FLR:3.0, Ori:278, Edges (Window/Level):6,	332.03	47.73	1,671,600.00	1,066,100.00	1,513,900.00	23.62	13.10	6,311,020,647.00	26.59
12	FLR:5.0, Ori:236, Edges (Window/Level):4,	334.96	48.47	1,715,900.00	1,099,900.00	1,433,100.00	20.42	10.16	6,663,756,885.00	27.30
13	FLR:3.0, Ori:197, Edges (Window/Level):8,	350.23	51.51	1,930,300.00	1,116,300.00	1,507,800.00	18.85	9.03	7,360,383,096.00	30.71



Phoenix	General Info	EUI	CUI	Lighting(sDA Based)	Lighting (Reduced LPD)	Lighting(+Dim/ Sched)	sDA	ASE	Total Lux Deficiency (from 300/point)	Carbon from Lighting /Area (lighting CUI)
1	FLR:11.0, Ori:227, Edges (Window/Level):6,	171.90	15.70	572,674.89	601,960.86	1,283,000.00	67.76	31.56	2,160,280,804.00	3.72
2	FLR:10.0, Ori:148, Edges (Window/Level):8,	175.00	16.01	571,662.20	724,610.49	1,145,100.00	56.10	24.70	2,175,828,890.00	3.72
3	FLR:12.0, Ori:142, Edges (Window/Level):4,	186.10	17.08	803,006.03	945,363.61	1,314,600.00	35.11	20.21	3,049,423,200.00	5.22
4	FLR:12.0, Ori:25, Edges (Window/Level):4,	187.10	17.20	847,236.71	902,293.46	1,193,800.00	39.20	17.96	3,194,879,640.00	5.51
5	FLR:8.0, Ori:78, Edges (Window/Level):8,	189.01	17.38	865,130.56	875,968.74	1,268,200.00	41.71	21.35	3,378,346,432.00	5.62
6	FLR:12.0, Ori:81, Edges (Window/Level):8,	189.52	17.41	817,202.72	804,062.03	1,155,900.00	48.54	24.66	3,183,627,216.00	5.31
7	FLR:4.0, Ori:41, Edges (Window/Level):12,	193.35	17.79	965,450.49	915,931.51	1,269,400.00	37.91	23.17	3,702,742,972.00	6.28
8	FLR:9.0, Ori:91, Edges (Window/Level):8,	199.92	18.42	1,078,500.00	940,228.89	1,114,400.00	35.59	15.83	4,215,519,432.00	7.01
9	FLR:5.0, Ori:174, Edges (Window/Level):6,	205.02	18.91	1,197,100.00	1,019,900.00	1,482,100.00	28.02	16.93	4,582,262,360.00	7.78
10	FLR:6.0, Ori:243, Edges (Window/Level):4,	214.83	19.87	1,283,800.00	932,468.41	1,475,800.00	36.33	23.75	4,891,984,104.00	8.34
11	FLR:3.0, Ori:260, Edges (Window/Level):12,	216.32	20.00	1,427,500.00	1,039,000.00	1,453,100.00	26.21	14.16	5,380,258,704.00	9.28
12	FLR:3.0, Ori:244, Edges (Window/Level):8,	221.60	20.51	1,507,900.00	1,061,800.00	1,486,500.00	24.03	13.59	5,692,713,384.00	9.80
13	FLR:7.0, Ori:103, Edges (Window/Level):4,	223.82	20.72	1,486,700.00	1,080,900.00	1,360,700.00	22.22	12.95	5,649,205,940.00	9.66

A.3 Baseline Project Example

Date: April 2016

Project Details		
Elementary School Example #001-2017		
Building Type	Education	Primary School
Location	City: El Paso	State: Texas
	Climate Zone	3B
Building Size	Gross Area	73,960 ft^2
	Dimensions	340' x 270'
	Floors	1 floor with 13 foot floor to floor height
Site	Orientation	North-east
	Context	Suburban

		Baseline Settings	*Notes*
Operations			
	Occupants	1,477 total occupants	
	Schedule	M-F, 95% 9am – 4pm, 15% 4pm – 9pm	
Envelope			
Exterior Walls	Steel-framed walls	Mtl studs 2 × 4 16" OC ASHRAE 90.1 Requirements Above grade non-res R = 13 + 3.8 c.i Non-res Ext. Wall U w/ film = 0.437 W/m^2-K = 0.077 Btu/h ft^2 F Reflectance = 0.30	Construction type: 2003 CBECS Data and PNNL's CBECS Study 2007 ASHRAE 90.1 Annual Building Utility Performance Summary.html
	Wall Sheathing	0.625" gyp board	Exterior Wall Layers: default 90.1 Layering
	Ext. finishing	0.75" Stucco	
	Interior finish	0.625" gyp board	
Roof	Built-up roof	Non-res, insulation entirely above deck ASHRAE 90.1 Requirements Non-res R = 20 c.i. Non-res roof U w/ film = 0.219 W/m^2-K = 0.039 Btu/h ft^2 F (No basement included in baseline)	Construction type: 2003 CBECS Data and PNNL's CBECS Study 2007. ASHRAE 90.1

(Continued)

		Baseline Settings	Notes
Windows	Windows Areas	Based on window fraction, location, glazing sill height, floor area and aspect ratio Operable area: 35%	PNNL's Glazing Market Data for ASHRAE spreadsheet
	Area of multiplied openings*	Total or average: 903.75 m^2 = 9,727.88 ft^2 North total or average: 324.80 m^2 = 3,496.12 ft^2 Non-north total or average: 578.95 m^2 = 6,231.77 ft^2	Annual Building Utility Performance Summary. html
	Glass U-factor*	average: 3.184 W/m^2-K = 0.561 Btu/h ft^2 F North average: 3.191 W/m^2-K = 0.562 Btu/h ft^2 F Non-north average:3.181 W/ m^2-K = 0.5602 Btu/h ft^2 F	Annual Building Utility Performance Summary. html
	Glass SHGC*	average: 0.221 North average: 0.218 Non-north average: 0.223	Annual Building Utility Performance Summary. html
	Glass visible transmittance*	average: 0.289 North average: 0.284 Non-north average: 0.291	* Totals/average also include skylight glazing
	Window properties	Non-res; vertical glazing, 30.1–40% Metal Framing (all other) U = 0.65 SHGC = 0.25	Score Card ASHRAE 90.1
Skylight	Dimensions	Gymnasium/multipurpose room Nine 4'×4' skylights total skylight area = 144 ft^2 = 3.75% of gym roof area Skylight with curb U = 1.30 SHGC = 0.34 U = 2.956 W/m^2 k = 0.521 Btu/h ft^2 F SHGC = 0.335	Score Card ASHRAE 90.1 Annual Building Utility Performance Summary. html
	Skylight Properties	Meet ASHRAE 90.1 Requirements Non-res; skylight with curb, glass, 2.1-5%	
Foundation	Slab-on-grade (unheated)	6" concrete slab poured directly on earth + Carpet Meet ASHRAE 90.1 Requirements Carpet and rubber pad R value = 1.23	Score Card ASHRAE 90.1

(Continued)

		Baseline Settings	*Notes*
		Concrete @ R = 0.0625/in – 6" = 0.38 U w/ film = 0.219 W/m^2-K = 0.219 Btu/h ft^2 F	Annual Building Utility Performance Summary. html
Infiltration	Air leakage	Peak: 0.2016 cfm/ft^2 of above grade exterior wall surface area (when fans turn off) Off-peak: 25% of peak infiltration rate (when fans turn on)	Reference: PNNL-18898: Infiltration Modeling Guidelines for Commercial Building Energy Analysis.
Internal Mass		6" standard wood 16.6 lb/ft^2	Score Card
HVAC			ASHRAE Ventilation Standard 62.1
	Heating type	1. Gas furnace inside packaged AC unit 2. Hot water from a gas boiler for heating	Score Card
	Cooling type	Packaged AC Unit	Score Card
	Fans	AC_2:5_unitary package =.85 m^3/s =1801 cfm AC_1:6_unitary package = 1.50 m^3/s = 3178 cfm AC_2:7_unitary package = 1.49 m^3/s = 3157 cfm	
	Ventilation	Total OSA ventilation = .339 cfm/ft^2	Score Card
	Central air capacity	Cooling coils nominal efficiency = 3.80 W/W	Annual Building Utility Performance Summary. html
	Heating capacity	Heating coils nominal efficiency = 0.80 W/W	Annual Building Utility Performance Summary. html
	Cooling set point	75°F	
	Heating set point	70°F	
	Cooling setback	80°F	
	Heating setback	60°F	
Lighting	Lighting power density (LPD)	Area weighted average of lighting = 1.19 W/ft^2 (More detailed schedule available in scorecard)	Score Card
Equipment	Appliances and equipment	Area weighted average plug and process load = 4.80 W/ft^2	Score Card

A.4 Baseline Setting Template

Date: ___________________

Project Details

Project Name

Number

Building Type	Commercial/Residential	Type
Location	City	State
	Climate Zone	#
Geometry	Gross Area	##,###
	Floors	# of floors ## foot floor to floor height
	Dimensions	L × W × H
Site	Orientation	
	Vegetation	
	Context	Urban, Suburban, Rural or None

		Baseline Model	Notes
Operations			
Occupants		Total	
Schedule		% occupancy each day of the week	
Envelope			
Exterior Walls			
Interzonal Wall			
Roof			
	Attic/Plenum		
Basement	Finished Basement		
	Unfinished basement		
	Slab		
Windows	Windows Areas		
	Window Properties		
Infiltration	Air Leakage		
	Ventilation Rate		
	Domestic Hot Water (DHW)		
	Humidity		
	Central Air Capacity		
	Cooling Efficiency		
	Heating Capacity		
	Heating Efficiency		

	Baseline Model	*Notes*
Operations		
	Cooling Set Point Heating Set Point	
Electrical		
Lighting	Lighting Power Density (LPD) Exterior Lighting Density Lighting Controls	
Equipment	Appliances and Equipment	

ACH = air changes per hour; SC = shading coefficient; HX = heat exchanger; MBH = 1000 Btu/hour; cfm = cubic feet per minute; c.i. = continuous insulation; UFAD = under floor air distribution; CV = constant volume; oc = on center; AHU = air handling unit; VAV = variable air volume; VFD = variable frequency drive.

A.5 Design Comparison Template

Date: ___________________

Project Details

Project Name

Number

Building Type	Commercial/Residential	Office
Location	City	State
	Climate Zone	#
Geometry	Gross Area	##,###
	Floors	# of floors ## foot floor to floor height
	Dimensions	L × W × H
Site	Orientation	East–West
	Vegetation	
	Context	Urban, Suburban, Rural or None

Comparison of Baseline versus Design				
Operations		***Baseline***	***Design Option***	***Notes***
Occupants				
Schedule				
Envelope				
Exterior Walls				
Interzonal Wall				
Roof	Roof Finish			
	Attic/Plenum			
Basement	Finished Basement			
	Unfinished basement			
	Slab			
Windows	Windows Areas			
	Window Properties			
Infiltration	Air Leakage			
Mechanical				
	Ventilation Rate			
	Domestic Hot Water (DHW)			
	Humidity			
	Central Air Capacity			
	Cooling Efficiency			
	Heating Capacity			
	Heating Efficiency			

(*Continued*)

	Comparison of Baseline versus Design			Notes
Operations		*Baseline*	*Design Option*	
	Cooling Set Point			
	Heating Set Point			
Electrical				
Lighting	Lighting Power Density (LPD)			
	Exterior Lighting Density			
	Lighting Controls			
Equipment	Appliances and Equipment			

Glossary

Active elements mechanical systems used in buildings to heat, cool, illuminate, and ventilate.

Algorithmic models predicated on an "if this then that" ruleset programmed into design software. The model can take time to set up, but it can simulate a large dataset quite efficiently.

Altitude angle comprises an angle off a horizontal plane to the sun's position in the sky, ranging from 0 to a zenith of 90 degrees.

American Recovery and Reinvestment Act commonly called the "stimulus," was designed to spur economic growth while creating new jobs and saving existing ones.

Annual energy costs the cost of operational building energy consumption from local tariffs and utility rate costs from energy fuel sources.

Annual energy use or **consumption** a combination of the annual heating and cooling loads, lighting, and equipment energy used for building operations.

Annual Sunlight Exposure (ASE) a measure of the space's annual exposure to direct sun that in excess causes glare.

Aspect ratio the two-dimensional relationship between a building's length and width.

Azimuth the measure of the sun's location on a horizontal plane as an angle where north is 0, east is 90, south is 180, west is 270, and north is again 360 degrees.

Baseline model a code-based BEM to investigate the standard reference design, which is a version of the proposed design that is minimally code-compliant and used to determine the maximum annual energy use requirement for compliance based on total building performance.

Bioclimatic a design that meets the human need for a comfortable interior environment tailored to the specific climate.

Brute Force Modeling (BFM) evaluates every possible combination of elements until it has exhausted all the possibilities.

Building Energy Modeling (BEM) a facet of BPS representing operational energy performance within a building.

Building Information Modeling (BIM) a digital representational process to generate and manage the physical and functional character of a building.

Building Performance Assessment (BPA) an early-stage model that focuses on various aspects of building design, giving value to and measuring the energy impacts of design decisions.

Building Performance Simulation (BPS) key abstractions representing functions of particular building elements.

Building science also known as Building physics, the study and analysis of building knowledge and experience to understand and control the physical phenomena affecting architecture.

Climate-adapted a building that incorporates passive environmental-control techniques to heat, cool, and ventilate to integrate the building within its climate.

Climate-rejecting a building that primarily relies on active systems—mechanical means—to heat, cool, and ventilate the building and where form and envelope serve solely as barriers between climate and conditioned space for environmental control purposes.

Climate zones geographical areas specific to ranges of temperature and humidity.

Continuous Daylight Autonomy (CDA) awards partial credit in a linear fashion to illumination values below the user-defined threshold.

Daylight autonomy (DA) a percentage of annual daytime hours a point in space is above the user-defined lux illumination level.

Daylight zoning relies on locating spaces that are suited for or require natural light in the appropriate location.

Design-dependent variables static building components related to conduction, solar, and ventilation, which change how the building relates to the exterior climate—primarily to the sun.

Design Performance Analysis (DPA) an early-stage model that focuses on various aspects of building design, giving value to and measuring the energy impacts of design decisions.

Dimming schedule a way to adjust a building's lighting power consumption through a set lighting schedule.

Discrete elements individual aspects of a building, such as a wall or window.

Dynamic components elements of the constructed building that change over time.

Energy Conservation and Production Act (EPCA) signed into law in 1975 by Gerald Ford, this was the first time that commercial and public buildings became a target for energy conservation.

Energy conservation measures (ECMs) commonly an operational activity, building element or technology used to reduce a building's energy consumption.

Energy Use Intensity (EUI) a reference number equal to the total annual energy use in kWh or MMBtus of energy consumed over the total building gross m^2 or ft^2 per year.

Equipment load the daily energy consumption of fixed items, such as the printers, copiers, and computers.

Fenestration the building's windows, frames, glass, and any shading devices.

Fuel mix the source of energy production used locally by the utility provider to provide the building with electrical energy; typically coal, natural gas, nuclear, hydropower, photovoltaic, and wind.

Genetic algorithm a computer-programmed routine that randomly selects the best potential option and moves it forward.

Geometric indices metrics used to quantify a building's geometry.

Global sensitivity analysis that describes how important a particular element is based on how many other elements it affects or that affect it.

Heating and cooling set points a set range of temperature variation allowed to maintain thermal comfort (the thermostat setting).

Home Energy Rating System (HERS) emerged from the RESNET organization formed from the insurance agencies responsible for evaluating energy efficiency in homes.

Hygrothermal refers to both moisture and heat.

Illumination the amount of visible light we see on a surface, measured in footcandles or lux.

Infiltration also called air leakage; the incidental and unintentional movement of air through gaps or cracks in the building envelope.

Internal load-dominated a building's energy consumption driven by the high density of occupants, lighting, and equipment requiring cooling year-round regardless of the climate.

Law of conservation of energy energy within the universe is always the same.

Law of entropy second law of thermodynamics; states that closed systems move to disorder over time.

Level of detail (development) (LOD) a term common in the use of BIM to describe the amount of information modeled during specific points of the design process.

Lifecycle cost the total cost of owning, operating, and maintaining a building over its economic life, including its fuel and energy costs.

Lighting power density (LPD) the predicted energy consumption in watts per square meter (W/m^2) or square foot (W/ft^2) of electric lights in a space.

Local sensitivity the statistical analysis of individual design elements or combinations of elements within an entire building system.

Luminous efficacy (lm/W) a measure of how well a light source produces visible light.

Lux deficiency method calculates the extra illumination needed for the points that do not meet the SDA requirements, but the energy needed to compensate for the lack of illumination is different in each case.

MacLeamy's curve the optimal project delivery relationship between cost and effort due to building information modeling.

Macroclimate the regional climate of a large area.

Massing a building geometry based on shape aggregation—piecing together similar or dissimilar shapes into a whole.

Microclimate the local set of weather conditions that differ from those of the surrounding area.

Non-design-dependent variables dynamic building components that are not design-specific, but material, construction, or technology dependent.

Occupancy schedule the percentage of the hourly schedule each day of the week, month, and year when people inhabit the building.

Occupant density the number of people in a space determined by the occupancy type and allowable density per code requirements.

Occupant load the number of people occupying the building.

One-at-a-time modeling investigation of one building element using BEM before moving onto the next item.

Parametric analysis an investigation of a set of ranges and their relationships.

Parametric model a programmed software routine with a specific logic to reach a solution.

Passive solar design the use of architecture and climate to provide heating, cooling, and ventilation without mechanical (active) systems.

Performance-based design where the form of a building is an expression of its energy performance.

Perimeter and core thermal zoning of a building based on different thermal comfort needs for the spaces near the exterior walls versus those near the middle or core of the building.

Plug loads the transient energy consumption loads users may plug in at their workspaces, such as a cell phone charger, fan, or laptop.

Program analysis also architectural programming; this involves defining the building scope and the type of building that the client, owner, or developer is looking for.

Psychrometry study of the mixture of water vapor and air, specifically its application in heating, ventilation, and air-conditioning, and meteorology.

Relative humidity (RH) what the body senses is the temperature related to the amount of moisture in the air.

Sandbox model a BEM used to get a feel for the modeling environment, a study model—sometimes called a white-box model—to conduct preliminary analysis of the building.

Sequential search technique a linear analysis method of possible options testing each one until the desired result is achieved or the list is exhausted.

Shape effect the combination of a building's orientation, aspect ratio, and stacking.

Shoebox model a typical representation of a small part of the building—perhaps just a typical room or a typical floorplate.

Simple-box method of starting the energy model using a a simple box about the size and shape of your building often using default data for HVAC systems and basic defaults for window–wall ratio, building geometry, and size.

Single zone a building with one thermal zone, either a room or an entire floorplate.

Skin-dominated building also known as an **external load-dominated** building; the energy exchange (the heat loss or gain) primarily occurs through the building envelope—its skin.

Solar gain the sun's contribution to the building's heating and cooling requirement.

Solar heat gain coefficient (SHGC) the glazing's efficacy at blocking the sun; expressed as a number from 0.1 to 1.0.

Space use the programmatic type of use in a building.

Spatial daylight autonomy (sDA) a measure of the annual usable daylight in a space.

Stacking a building's vertical proportion and the number of floors, which increases as the building grows in height.

Static components parts of a BEM that, once built, will not change, such as the walls, roof, and window elements.

Surface reflectance a material's efficacy at reflecting solar energy.

Thermal buffer spaces that help to mediate between internal and external thermal conditions.

Thermal comfort a subjective expression of a building occupant's satisfaction with the interior environment.

Thermal conductance commonly known as its U-factor, refers to the amount of heat that passes through a material.

Thermal mass refers to a material's ability to absorb solar radiation and store it for later use.

Thermal storage space A space used to store excess heat from higher thermal zones to use at different times of the day or night or in other areas of the building, essentially reusing the heat created by the building operation systems.

Thermal zone a BEM element containing spatial properties related to use, occupancy schedule, operation, energy consumption, and thermal comfort settings.

Thermal zoning considers the location of spaces based on heating and cooling needs to take advantage of synergies.

Utility cost what the local energy (electricity or gas) provider charges per unit of energy consumed.

Visible transmittance (VT) the fraction of visible light that passes through a window.

Weather files temperature, humidity, precipitation, and solar radiation data used to represent a historic picture of climate conditions for a specific location.

Whole building energy model (WBEM) the building performance simulation of all operational energy consumed within a building.

Zero energy performance index (zEPI) a scalar measurement of a building's energy consumption related to its ability to achieve zero energy use.

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