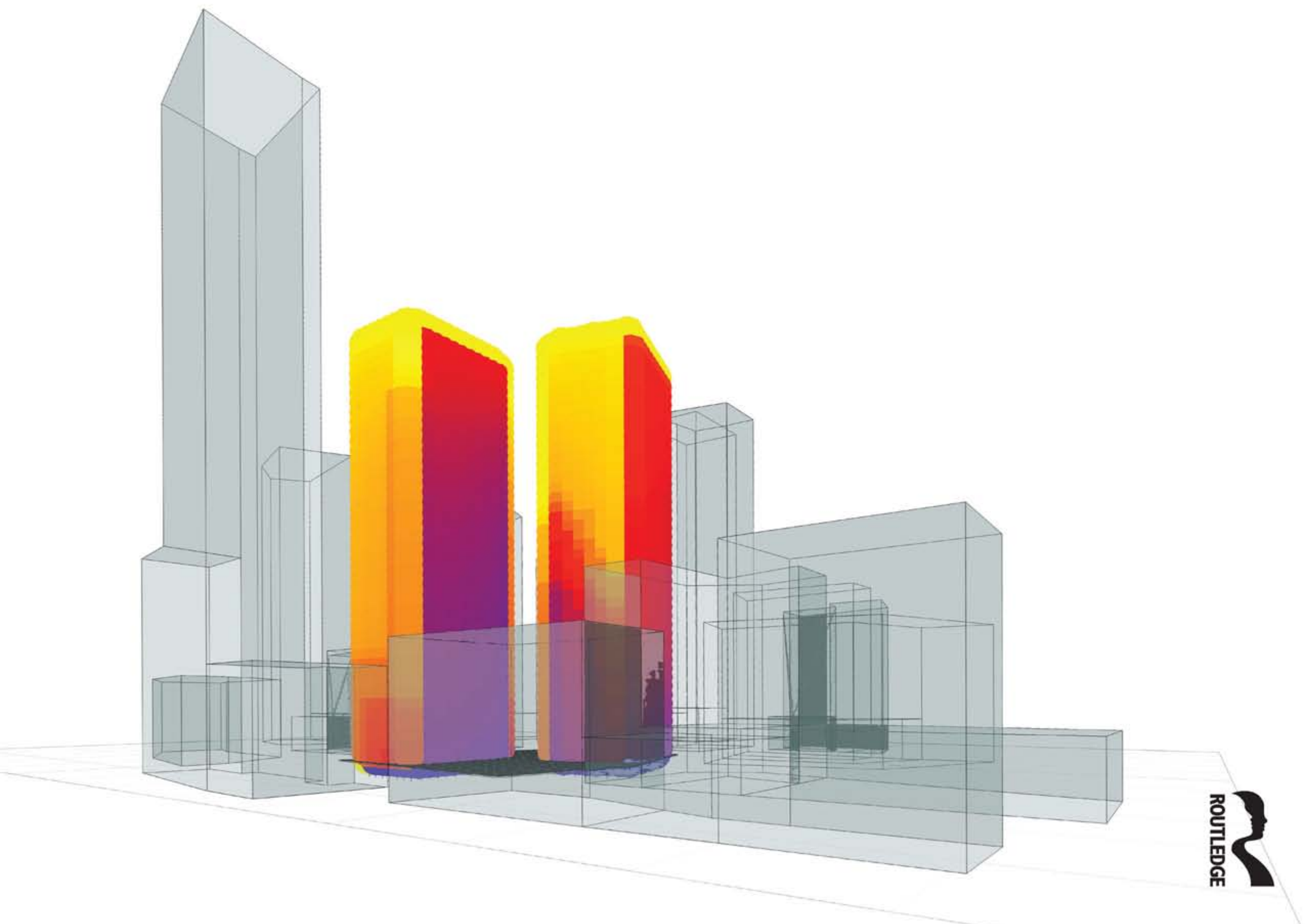
Kjell Anderson

DESIGN ENERGY SIMULATION FOR ARCHITECTS

GUIDE TO 3D GRAPHICS



ROUTLEDGE

Design Energy Simulation for Architects

Leading architectural firms are now using in-house design simulation to help make more sustainable design decisions. Taking advantage of these new tools requires understanding of what can be done with simulation, how to do it, and how to interpret the results.

This software-agnostic book, which is intended for you to use as a professional architect, shows you how to reduce the energy use of all buildings using simulation for shading, daylighting, airflow, and energy modeling. Written by a practicing architect who specializes in design simulation, the book includes 30 case studies of net-zero buildings, as well as of projects with less lofty goals, to demonstrate how energy simulation has helped designers make early decisions.

Within each case study, author Kjell Anderson mentions the software used, how the simulation was set up, and how the project team used the simulation to make design decisions. Chapters and case studies are written so that you learn general concepts without being tied to particular software. Each chapter builds on the theory from previous chapters, includes a summary of concept-level hand calculations (if applicable), and gives comprehensive explanations with graphic examples. Additional topics include simulation basics, comfort, climate analysis, a discussion on how simulation is integrated into some firms, and an overview of some popular design simulation software.

Kjell Anderson practices at LMN Architects in Seattle, Washington, USA.

"Kjell's writing manages to blend high-level overview with detailed specifics in a way that is both engaging and illuminating. His significant practical experience, as well as that of his interviewees, makes this book a unique and valuable contribution to the world of energy modeling and simulation."

Andrew Marsh, creator of Ecotect

"Anderson has curated the best examples of how architects can engage with building performance simulation tools early and often throughout the design process."

Heather Gayle Holdridge, Sustainability Manager at Lake Flato Architects

"By an architect for architects, this book is accessible, clear and visually informative—the modeling roadmap we've been waiting for!"

Margaret Montgomery, Sustainable Design Leader at NBBJ

"Anderson offers a compelling overview of energy modeling for architects, encouraging incorporation of natural energy strategies leading to a significant reduction of carbon emissions."

Edward Mazria, Founder and CEO of Architecture 2030

"An essential desktop reference for any architect hoping to incorporate simulation into their arsenal, this book highlights how to use evidence-based approaches to achieve high-performance and design excellence."

Blake Jackson, Sustainability Practice Leader at Tsoi Kobus and Associates

Design Energy Simulation for Architects

Guide to 3D graphics

Kjell Anderson

Routledge
Taylor & Francis Group
NEW YORK AND LONDON

First published 2014
by Routledge
711 Third Avenue, New York, NY 10017

and by Routledge
2 Park Square, Milton Park, Abingdon, Oxon OX14 4RN

Routledge is an imprint of the Taylor & Francis Group, an informa business

Library of Congress Cataloging in Publication Data
Anderson, Kjell.
Design energy simulation for architects: guide to 3D graphics/
Kjell Anderson.
pages cm
Includes bibliographical references and index.
1. Sustainable buildings–Design and construction–
Data processing. 2. Architecture and energy conservation.
3. Buildings–Energy conservation–Computer simulation.
4. Three-dimensional display systems.
I. Title. H880.A53 2014
720′.472028566—dc23 2013025925

ISBN: 978-0-415-84065-1 (hbk)
ISBN: 978-0-415-84066-8 (pbk)
ISBN: 978-1-315-85143-3 (ebk)

Acquisition Editor: Wendy Fuller
Editorial Assistant: Laura Williamson
Production Editor: Siobhán Greaney
Typeset in Syntax
by Florence Production Ltd, Stoodleigh, Devon, UK

Contents

Figures

Acknowledgments

This book would not be possible without the sustainability leadership at Callison. Cindy Davis, Steve Harmon, Matthias Olt, and many others helped create an environment where my interest in sustainability was encouraged to be both wide-ranging and practical. From climate analysis through the creation of an in-house energy modeling program to presenting our work at Greenbuild and writing this book, Callison provided a proving ground.

I would also like to thank LMN Architects for providing my next challenge, as well as for sharing simulation expertise via the LMNts blog. The sharing of information marks a stark contrast with an older mentality, and betters the practice of design and sustainability.

My wife, Jamie Anderson, encouraged me to write the book, supported me, and redlined the entire book a couple of times—I can't thank you enough. I'd also like to thank those who provided in-depth interviews or reviewed the book for accuracy and readability: Christopher Meek, Brian Skripac, Albert Sawano, Edward Dean, Anton Toth, Chris Olmstead, Eddy Santosa, Heather Holdridge, Jason McLennan, Jeff Niemasz, Jeremiah Crossett, Jim Burton, Chris Hellstern, Jim Hanford, Marc Brune, Lisa Petterson, Mark Perepelitza, Mika Yagi, Alexandra Ramsden, Mike Eliason, Aaron Yankauskas, Matt Peterman, Sam Miller, Scott Crawford, Premnath Sundharam, Nicholas Long, Olivier Pennetier, Shawn Oram, Tom Marseille, Stuart Hand, Maurya McClintock, Tom Marseille, Amarpreet Sethi, Mark Adams, Jens Voshage, Jason Hewitt, Teresa Burrelsman, Gabriel Greiner, Chris Chatto, Michelle Linden, Amal Kissoondyal, and Martin Brennan.

This book is dedicated to my daughters, Carmen and Lena. I hope that the earth you inherit will be peaceful and verdant.

Conversions of Common Energy Modeling Units

From Inch-Pound (IP) to the International System (SI)

1 footcandle	=	10.76 Lux (illuminance; most practitioners assume 1 footcandle = 10 Lux)
1 Btu/h/ft^2	=	3.16 Watts/m^2 (instantaneous power incident on a surface)
1 Btu/ft^2	=	3.16 Watts* hours/m^2 (units of energy on a surface over time)
1 Btu	=	.293 Wh (unit of energy)
kBtu/ft^2/year	=	11.352 MegaJoules/m^2/year (Energy Use Intensity, annual measure of energy use per unit area)
1 W/ft^2	=	.093 W/m^2 (Plug Load or Lighting Power Density, usually per room area)
U value (Btu/ft^2/h/°F)	=	5.678 U value (W/m^2/°C) (conductivity of a material or assembly, where U = 1/R)
1 ft^2/minute	=	.000472 m^2/second (air change rate due to infiltration or fresh air supply)
1 Foot/second	=	.681 miles/hour = .3048 m/second = 1.097 km/hour (speed, often in relation to airspeed)
°F	=	(5/9)°C + 32 (Temperature)

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1

Introduction

Design is not just what it looks like and feels like. Design is how it works.

—Steve Jobs

Today few reasonable people doubt that human actions are changing our climate. We are not only changing nature, but also reducing nature's ability to provide the clean air, water, and sustenance that we all rely on. While the overall change in climate is slow, the effects are felt suddenly, when rivers that supply millions with water flood or run dry, when hurricanes reach areas where they have rarely been experienced before. We've seen these effects increasing over the past 50 years.

From more extreme storms that level coastlines to droughts that affect food availability and prices, our climates are changing. The generation on this planet now has the unique opportunity to change course and avert the worst effects of climate change, which would otherwise surely lead to more climate refugees, more human suffering, and more wars.

The building industry accounts for nearly half of energy use in the US, and around 70% of electricity use. From researching and drawing up master plans, to block-scale design, to building design and construction, to operations, each section of the industry needs to achieve better performance. Shifting the burden of addressing climate change to future generations is irresponsible.

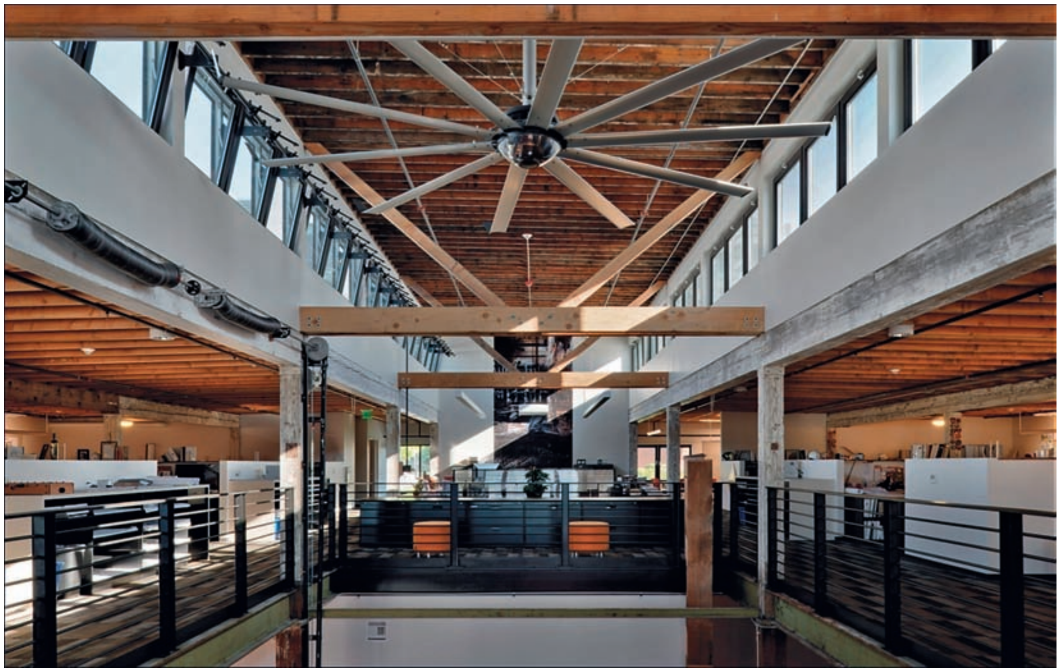
We live in an era where data is abundant, yet very little of this data is used to effectively inform the early design of buildings, when the right moves can reduce future energy consumption significantly with very little additional cost. Early geometries are rarely compared for energy use, daylighting, shading, or airflow potential, since there are many other issues for architects to consider.

There are many leading firms, however, that have learned the value of these studies to help them make better decisions. This field, called design simulation, applies data to building design, incorporating the rigor of energy modeling with quick studies and graphic, intelligible outputs that can influence decisions among the chaos of early design. This field includes both traditional energy modeling as a compliance tool, but also incorporates front-end modeling, including comfort, solar radiation, daylight, airflow, and shoebox modeling.

As an example, the four-story offices of Rice Fergus Miller (RFM), built for $105 per square foot in Bremerton, Washington, use 90% less energy than the national average, only 160 solar panels short of achieving Net Zero Energy (see Figure 1.1). The project follows a new paradigm: setting high goals early, using an engineer-integrated process, maximizing daylight, using natural ventilation when possible, limiting glazing area, maximizing insulation, and validating each of these design decisions with a combination of design simulation and experience.

While it uses an advanced mechanical system, the system cost only $10 per square foot—an exceptionally low amount. The system cost less because the architecture maximized the portion of the year when the system was unnecessary or only minimally necessary because it was smaller and used "off-the-shelf" components.

Since Leadership in Energy and Environmental Design (LEED) was introduced in 1998, the industry knowledge of sustainability has improved significantly. However, in many cases architects are still designing the same building geometry and façade as they did pre-LEED, relying on specification changes and



1.1

The Rice Fergus Miller offices in Bremerton, WA, were completed with an energy use intensity 90% below average for a cost of \$105/ft^2 in an existing building using off-the-shelf technology. An integrated team using design simulation to inform early decisions made this possible. See Case Study 10.5.

Source: Photo: Courtesy of Rice Fergus Miller Architects.

mechanical systems to improve energy performance. This is not cost effective and does not achieve the deep green energy savings that the 2030 Challenge requires. It also leads to the perception that green buildings cost much more.

While this book is not about costs, it is about a design process that helps architects make better decisions in the early phases of a project, instead of adding expensive technology at the end of it.

Our profession needs to re-invest in knowledge about our buildings' performance. One of the best strategies is to begin engaging in design simulation and becoming more knowledgeable about energy use and energy modeling. We will soon look back on the days before architects engaged in design simulation with surprise, wondering how it was possible to so radically divorce design from performance.

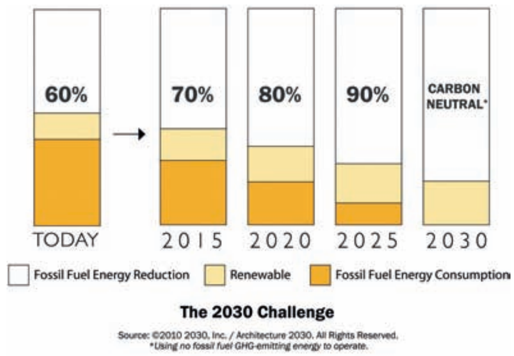
DESIGN FOR NEGA-WATTS

In terms of societal cost, it is much cheaper to reduce energy use through design and retrofit (sometimes referred to as nega-watts, as a play on mega-watts) than it is to increase energy production. For this reason, informed building design is one of the least expensive pieces of an overall strategy to minimize energy use and associated climate change. While subsidies are given for lighting retrofits, to create new wind and nuclear power and to add renewable energy to buildings, puzzlingly little is spent on assisting architects with the early design process.

While some posit that the main solution to climate change will be widespread use of hydrogen, electric cars, a smart grid or other technologies, the design and retrofit of individual buildings offer an immediate and proven method of reducing carbon emissions. While most technologies last 10 or 20 years, the early design process involves decisions that affect energy use over the life of each building, perhaps 150 years.

When studying a client's program, an architect will often sketch options. This act begins to associate space, geometry, and proportion with a program, and deepens the architect's understanding of the site, the program, and the massing possibilities allowing them to make informed decisions.

Similarly, doing quick design simulations deepens an architect's understanding of how energy and daylight performance are affected by geometric options within a given climate. The simple act of testing a space using design simulation builds an intuitive understanding of performance that can be used immediately, through later design iterations, and on future projects.



1.2

The 2030 Challenge sets decreasing energy use targets for new buildings, with a goal of Net Zero Energy (NZE) by the year 2030. Reduction percentage is in relation to the 2003 CBECS survey.

Source: Courtesy of 2030 Challenge.

THE 2030 CHALLENGE

Ed Mazria's 2030 Challenge lays out a path to reducing our contribution to climate change. It is ambitious, targeting all new buildings to be Net Zero Energy (NZE) by 2030. Many organizations have signed on, believing it is necessary and can be done, including the US General Services Administration, which oversees the construction of federal buildings, the American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE), as well as firms throughout the design and construction industry.

While some of the focus of the 2030 Challenge is on renewable energy, most of the energy reductions are due to better design. Building materials, systems, and methods already exist to meet the 2030 Challenge—they simply need to be organized properly by project teams through the design process. The right design requires evaluation and validation throughout each project, the subject of which constitutes this book.

The movement to reduce building energy use, which accounts for around 40% of global greenhouse gas emissions, will not be led by governments. If we succeed in reducing our energy use, it will be due to the passion of the researchers, professionals, and citizens who avoid both the cynic's easy perch and the willful ignorance of their impact. Those who, like Thomas Jefferson, consider any burden they place on future generations to be immoral are already on board.

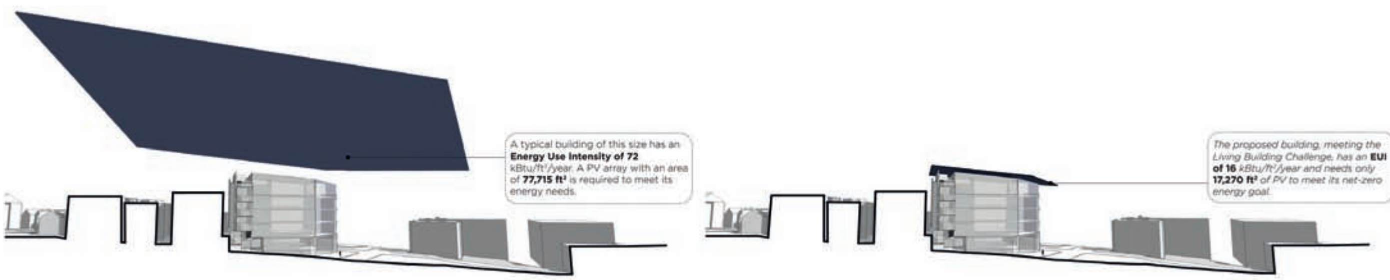
ARCHITECTS + ENERGY MODELING?

Energy modeling began as a method of sizing cooling and heating equipment for buildings, and has been primarily practiced alongside mechanical engineering. Architects have relied on engineers to understand and provide building comfort so much that in the middle of the twentieth century they began to abandon the art of designing rational climate responses. Comfort and lighting became the exclusive territory of engineers—their tools for providing comfort using energy have become very sophisticated. The tools to help architects make better passive decisions during early design are embarrassingly less so.

While design simulation is often seen as a specialist's tool for predicting energy performance, the greatest value for architects is the freedom to play with design ideas and receive timely feedback. Instead of applying generic sustainable strategies that the architect doesn't fully understand, design simulation allows options to be quickly tested to achieve the project team's design and sustainability goals.

While there are risks in including architects in the design simulation process, the risk of continuing to exclude them is far greater. The present task of averting the worst effects of global warming is immediate and requires architects to engage fully in energy-conscious design. The need is apparent—with this book and many other efforts, the tools to succeed are also available.

Architects are uniquely positioned to affect passive strategies in their designs. They need to have the means to evaluate design decisions to take advantage of this, however. An in-house design simulation program offers the ability to have some early design decisions evaluated or validated within a day's time.



1.3

The left image shows a solar photovoltaic array extent required to meet the annual energy needs of a typical office building the same size as the Bullitt Center in Seattle. Using an integrated approach, asking the right questions, and evaluating decisions using experience and simulation, the array necessary to achieve Net Zero Energy was reduced to fit on site.

Source: Courtesy of Miller Hull.

EARLY DESIGN SIMULATION

Early design simulation includes studies on solar energy, daylighting, airflow, and energy use that inform the site planning and conceptual design phases. This new field has been taken up by many of the leading firms, who can see the benefit of informing and validating design decisions from within the design process.

Even firms that have in-house engineering capabilities, such as Skidmore, Owings, & Merrill and DLR Group, have a cadre of architects and analysts who specialize in early design simulations who are nimble enough to perform useful simulations for project teams in early design. They have found that this connects energy performance directly to architectural design and improves the resulting building performance.

Currently, architects are nearly excluded from energy evaluations of their buildings, just as mechanical designers are nearly excluded from the geometrical design process that their systems respond to. This results in many of the most effective energy reduction strategies not being on the table before the full team is assembled, while only the more costly system upgrades remain. Effective design for natural ventilation, daylighting, and solar orientation requires early design decisions that can be informed by experience and analyses.

On an integrated project team that includes architects and engineers from the outset, some modeling is best done within an architecture firm and some is best done by the engineering firm. For the Bullitt Center in Seattle, the architects Miller Hull did early daylight modeling that compared a courtyard scheme to a more compact scheme, and also proved the necessity of increasing the floor-to-floor height to achieve daylighting goals. PAE Engineers handled more specialized early modeling. The project is expected to be the largest Living Building Certified project, see Case Studies 7.6, 9.2, and 10.7.

Simulation software is now intuitive, graphic, and well enough designed to be useful to architects. With the basic guidance and the examples contained in this book, architects should be able to begin to engage in many types of useful simulations, and learn when they need to bring in specialists.

Some advantages of in-house design simulation are:

- Once architects are involved in a number of simulations, they gain an intuitive understanding of how their designs can affect light, heat, and airflow.
- Quick analyses can be done in a matter of hours by trained architects or specialists, depending on the complexity of the analysis.
- In-house design simulation makes architects think about energy use, and the concepts covered allow them to speak more fluently to engineers about later-phase design simulation.
- Open-ended software allows the team to answer general or specific questions about a design's performance. It allows a detailed comparison of design options, and gives the ability to test ideas in real time while designing.
- Many analyses produce results that are mapped graphically onto a 3D model. Intuitive designers are quickly able to grasp the implications of an option, and craft a response to the analysis.

1.4

The Net Zero Energy offices for DPR Construction in San Diego, designed by Callison as part of an integrated project team, used simulation to inform strategies such as natural ventilation, daylighting with light tubes and light-diffusing tensile fabric, skylights, large fans to circulate air, and an advanced understanding of thermal comfort using the adaptive thermal comfort model.

Source: Image © Hewitt Garrison Photography.

> Good graphics cut across communication barriers, and offer proof of design concepts through all design phases.

Design simulation can also keep the architect from recommending the wrong strategies. CBT Architects in Boston related a story where ostensibly green strategies costing over $1 million were going to hurt, or at least not help, energy performance: light shelves, low-SHGC glazing, additional insulation, and others. Money saved in these areas was diverted to more impactful systems. Many other firms alluded to similar studies showing that a "green" strategy was not appropriate for a specific building. The sensitivity analysis shown in Case Study 10.3 can help a project team determine the most impactful energy strategies at project outset.

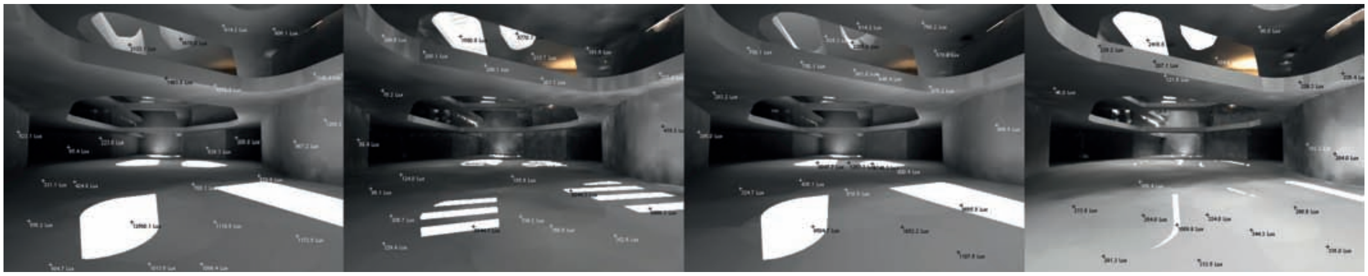
THE STRUCTURE OF THE BOOK

This book is about the use of design simulation tools within architectural practice. It presents a theory that architects should design higher-performing buildings when they actively engage in design simulation. Even without a formal understanding of how solar energy, lighting, airflow, and HVAC systems interact, an understanding of the effects of design moves on energy performance will be developed by using design simulation.

With that premise, this book focuses on developing architects' understanding of, and appreciation for, design simulation. It attempts to answer the questions:

What can design simulation do?
How have firms used it?
How are the results interpreted?

In this book 30 case studies illustrate the range of what can be studied with design simulation, each focusing on a different method of analyzing a building's performance. Since it is aimed at early design,



1.5

Daylight simulations were used to compare and evaluate several skylight geometries for this retail atrium in Wuxi, China. Each option was evaluated under both sunny and overcast skies to determine the best mix of ambient light, direct light, and minimization of glare.

Source: Courtesy of Callison.

this book showcases the validity of simulation that does not focus on proving the cost or energy savings with every simulation.

Most case studies were chosen to represent the common analysis types an architect will perform or request in early design, with the others providing elegant solutions to complex problems or validating earlier simulation work. Each case study describes the software, techniques, and unique inputs used, and helps the reader interpret the results. The preceding chapter contains theory and additional examples that illustrate the concepts necessary to understand, perform and interpret a design simulation.

While many books are full of strategies, this book highlights tools and methods to evaluate and optimize strategies to reduce peak and annual energy use. This book does not offer the proverbial fish, but offers guidance in fishing.

Charts and load tables are not listed in this book. They are found in first-source references books such as those from the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE), the International Building Performance Simulation Association (IBSPA), the US Department of Energy (DOE) and others in print and on the internet.

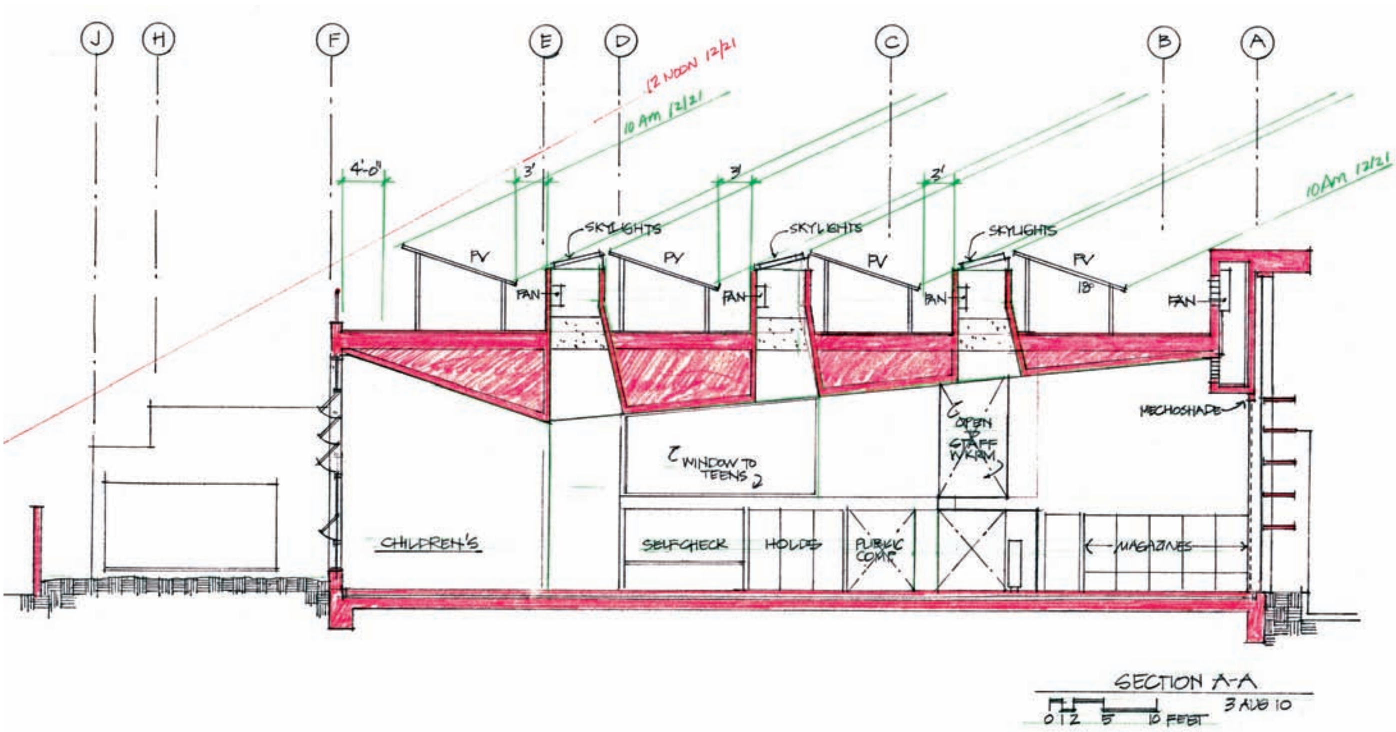
The 50+ individuals I have interviewed for this book represent a wave of professionals who know that the time has come for early stage design simulation to be part of every design project and every design firm. They know that once architects step into simulation, the knowledge they gain will improve their ability to design low-energy buildings.

This book intentionally limits the scope to simulation of direct energy use. Water use, air quality, embodied energy, and other important topics are necessarily excluded. While holistic design is the goal, a single book attempting to incorporate all necessary knowledge for holistic design would be of infinite length. The design team, not the books, need to be holistic in their scope.

CONCLUSION

The new paradigm of architects engaging in the energy simulation of their buildings is necessary to achieve higher levels of building performance. Even as part of the integrated design process, architects are best served by doing some simulations internally so decisions can be made quickly. This book lays the foundations for those simulations, and introduces newcomers to the broader world of building performance. A paper presented at the International Building Performance Simulation Association (IBSPA) 2009[MD1] describes the challenges of architects using design simulation in more detail (Bambardekar and Poershke, 2009).

The author is not proposing that every design move be verified with design simulation. However, once design simulation becomes part of the normal working process, architects will begin to understand the underlying interactions and can make intuitive design moves with the confidence that they will lead to a low-energy building.



1.6

Early design section through the reading room of the Net Zero Energy-designed West Berkeley Library. The design team used a combination of intuition and design simulation to create a roof form that correctly balanced the space for renewable energy, deep light wells, and natural ventilation. See case studies 8.2 and 9.1.

Source: Concept sketch by Edward Dean, courtesy of Harley Ellis Devereaux Architects.

2

Design Simulation Basics

A great building must begin with the unmeasurable, must go through measurable means when it is being designed and in the end must be unmeasurable.

—Louis Kahn

We live in a data-driven world. Many architects, however, are intuitive. We react to graphically presented information much more naturally than tables of numbers. Since architecture is an applied field, we also respond better to information that is specifically applicable to our projects. Graphical, project-specific feedback is the cornerstone of design simulation software, allowing architects to integrate it into the design process.

By using design simulation, architects can begin to understand the effects of their design moves on energy use. While architects are not formally trained in the underlying calculations, a general intuition about daylighting, solar energy, massing, and other factors can be developed, helping them become better at the practice of high-performance architecture.

This chapter will introduce architects to the concepts and basics of design simulation, used throughout the chapters.

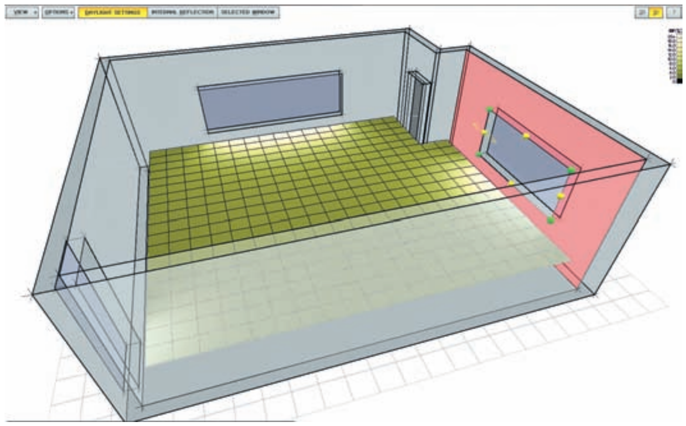
ASKING THE RIGHT QUESTIONS

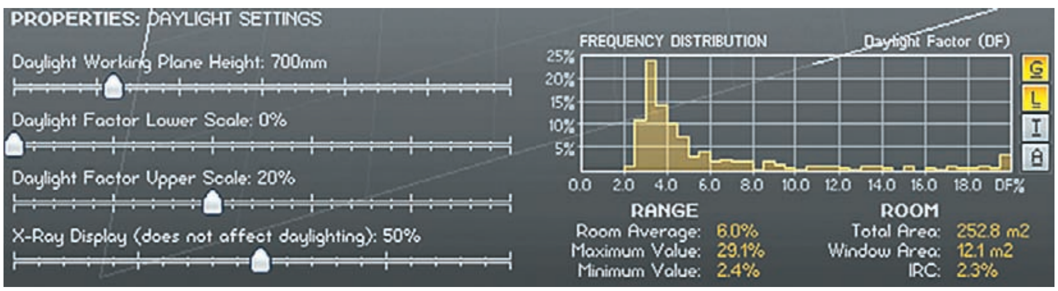
The use of design simulation requires that questions are asked throughout the design process. The best questions are simple—perhaps,"How much skylight glass is necessary to daylight this atrium?" This question will be answered very differently from "What orientation of the skylight glass produces the most even balance of light within this atrium?" Architects are experienced in asking the most crucial questions in early design—asking the right energy use questions requires some additional experience,

2.1 and 2.2

Lake Flato Architects, along with the University of Washington Integrated Design Lab (UW IDL), Sheply Bulfinch Architects and Clanton and Associates (Lighting) held a two-day design charette on daylighting and lighting design for the Austin Central Library. They inspected the models under sunny skies to compare daylighting options and discuss how electric lighting can add to the effects. See Case Study 8.3 for more information.

Source: Photos courtesy of UW IDL.





2.3 and 2.4

Andrew Marsh, creator of Ecotect, has been experimenting with real-time, on-line daylighting simulation. The room and windows can be adjusted to see real-time daylight factor results.

Source: Courtesy of Andrew Marsh. http://andrewmarsh.com/blog/2010/04/11/real-time-dynamic-daylighting.

though. Each of the case studies contains at least one important question, and presents a process to answer it.

The question needs to be framed so it can be answered by research or design simulation software. In the first question above, the team may design four options, and test which of them provides enough, but not too much, daylight. The team can answer the question with a quick 3D model with material assignments, the right software or physical simulation, and some experience or guidance. Two of the options may be fairly successful, which may be combined to test a fifth option, or the simulation may inspire other ideas that lead in new directions.

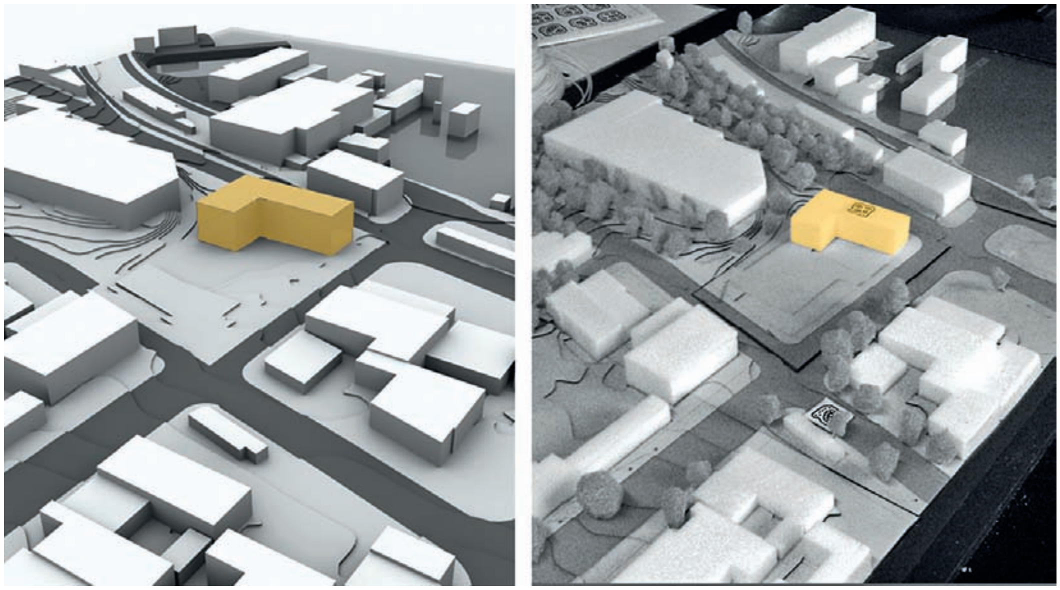
This process is similar to the scientific process, which involves asking a question, framing a solvable experiment to answer the question, testing, and interpreting the results. While the scientific process sounds too sterile for the multitude of inputs into the early design process, it can often be done in a matter of hours, providing useful feedback.

PLAY LEADS TO UNDERSTANDING

In addition to providing immediate feedback about a design option, the process of answering questions with design simulation leads to an understanding of causality—which design decisions affect performance significantly and which ones affect it less so—specific to the climate, typology, and site.

Since simulations provide immediate feedback about the consequences of design decisions, continued use of simulation software validates and hones an individual's intuition regarding the effects of design moves on energy use. Even without the knowledge of the complex underlying algorithms, architects can internalize a sense of how forces interact. Continued application of real-time, iterative software can teach the intuitive nature of designers much easier than the memorization of charts and equations.

In fact, most professional energy modeling is based on the "trade-off," where one element is swapped for another to determine the effects. After many trade-offs have been tested, the analyst begins to understand how changing a single element can affect the system, becoming aware of those things that most affect energy use.



2.5

LMN Architects are exploring a link that allows physical models to be instantly linked to computer-based simulations. The physical model on the right contains a tag. The location and orientation of the tag are read into the computer, which can then instantly assign attributes and run simulations. Many of these tags can be applied, leading to a real-time link between the modification or rotation of a physical model and the ability to assess the energy, solar, or daylighting ramifications of the move. LMN used the Reactivision Listener for Firefly, a plug-in for Grasshopper, to create this link.

Source: http://lmnts.lmnarchitects.com/interaction/tangible-user-interfaces/.

With current and near-future software, daylighting, energy, and other types of design simulations can take on these qualities, very similar to how we learn through play. Some examples of how this is being explored are given below:

- Dr. Andrew Marsh, creator of Ecotect software, is currently working on a real-time daylighting application where the user can stretch and collapse windows and see real-time daylighting results. A real-time shading calculator is found on his blog as well.
- The Online Comfort Tool from Berkeley allows the user to play with environmental conditions in real time, giving the user a sense of the extent to which variables affect one another. This is discussed in Chapter 3.
- LMN Architects created a system to pre-run hundreds of highly accurate lighting simulations—once the calculations are done, the results can be navigated in real time to determine optimum window sizes and locations for daylighting.
- A study on the use of play to promote energy decision-making found that students understood and enjoyed the use of design simulation (EnergyPlus, in this case), when framed in the context of play (Reinhart *et al*., 2012[MD2]).

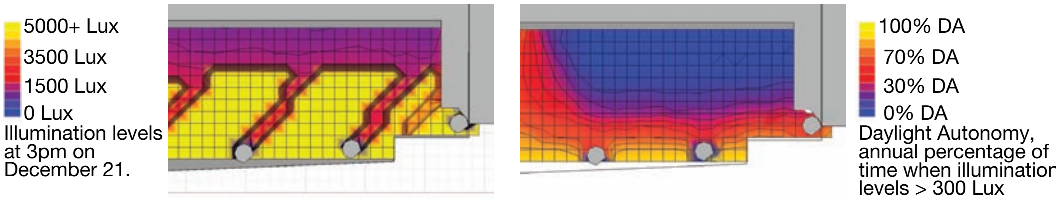
Play can also influence user behavior: Chapter 3 discusses real-time feedback for building occupants which instructs them, based on similar principles.

Accuracy is important when performing iterative design simulations; otherwise the simulator is simply learning to game the system to achieve good results. Simulation accuracy, as discussed in Chapter 11, is partly based on the number of iterations a simulation is run through, giving the simulator time to calibrate the results with their research and expectations.

TERMINOLOGY AND CONCEPTS

Asking and answering questions using design simulation requires a basic understanding of some of common terminology and concepts, as detailed below.

A design option is often compared against a *baseline* option or assumption to determine any performance improvement. Although standards exist for some baselines, choosing a baseline can be difficult. In many cases, it is based on research but nonetheless is still somewhat arbitrary. For example, if the project team uses a baseline where a third of an office building's lighting will be left on all night, then occupancy sensors may be shown to provide 50% lighting energy savings annually, with a return



2.6

Plan view of an open office space, showing a façade with columns at the bottom. A point-in-time (PIT) analysis (left) provides information about daylight levels and potential for glare at 3:00 p.m. on the winter solstice, for example. An annual daylight autonomy analysis (right) shows areas that are successfully daylit for a certain percentage of the year. Both use false colors to illustrate lighting levels; they are Autodesk Ecotect outputs of Radiance and Daysim analyses, respectively.

on investment of 3 years. If the project team assumes that occupants will turn off the lights when they leave at night, occupancy sensors may only be projected to reduce lighting energy use by 20%, with a return on investment of 10 years. As a broader example, ASHRAE 90.1's baseline building energy use is unique to every design, leading to industry-wide misunderstanding regarding a building's modeled and actual energy performance.

Point-In-Time analyses are run for a single moment in time, while *Time-step* analyses are run over a time period such as a year. We live our lives as a sequence of points in time—light levels and temperatures need to meet our expectations at each of these points in time or else occupants complain or attempt to modify the building systems to restore comfort. Studying a point-in-time (PIT) is useful for peak heating and cooling loads, thermal comfort, and glare. A point-in-time (PIT) analysis can be very accurate and can be run fairly quickly. To determine trends through time, however, many analyses must be run.

A time-step analysis performs a sequence of analyses, based on many assumptions about building use, connecting them to form an overall assessment. The time-step could be a minute, an hour, a day, or other increment, though often they are run at each hour over a year. This allows analyses to use data that is averaged over the time-step, which often simplifies calculations. ASHRAE 90.1 Energy trade-offs for Energy Code or LEED credits and predicted Energy Use Intensity (EUI) are based on annual time-step simulations.

Since glare, temperature, and other conditions for each time-step are typically averaged over an hour, accuracy is not as great as with a PIT analysis. The time-step can be shortened, but this increases the run-time for each simulation.

Run-time refers to the amount of time a computer requires to produce a simulation result. A run-time of under a minute gives the user good feedback and allows many simulations (called *iterations*) to be run to calibrate and understand the results. A run-time of an hour or longer requires the simulator to move on to another task while they wait for results, disrupting the train of thought. Accuracy of a simulation is partly dependent on the number of sequential iterations that a user runs, since each allows another chance to calibrate the results, meaning that a short run-time can increase accuracy.

Level of detail. One of the trickiest aspects of design simulation is determining the right level of geometric detail for each analysis. Most analyses are made computationally feasible only by reducing the number of geometric elements significantly: mullions, window frames, wall thicknesses, and other detailed items are often abstracted or eliminated. In the author's experience, stripping down a 3D model, or building a new one, takes at least half the time allotted for most design simulations.

An *input* refers to a parameter entered by the user, such as a glazing property, the color or reflectance of a wall covering, or a schedule of when people will be in the building. Inputs are changed to test various options in design simulation.

Default values are inputs that are suggested by the software, usually based on industry norms. For example, DIVA software suggests that typical walls will reflect 50% of light and floors will reflect 20% of light. The inputs are easy to change when the project team has more accurate information, but for most early design simulations the defaults result in a reasonably accurate simulation.

Parametric software allows users to dynamically change inputs that affect the model's geometry or properties. As an example, the user could increase the floor-to-floor height with a single input and the rest of the building would be automatically adjusted to meet this parameter. Parametric modeling is very powerful in design simulation as it can be used to quickly compare performance among many options.

Boundary conditions are assigned to create outer 'edges' of a simulation when studying a portion of a building. This limits the geometric scope and run-time of a simulation, allowing questions to be answered more quickly. For instance, a daylight simulation may look only at the west-facing façade or a single office within a building, so geometry for the rest of the building does not need to be considered. A shoebox energy model may include a typical bay within an office or retail façade, using boundary walls that transfer no heat to decrease the run-time.

In physical daylighting models, light *sensors* are placed within a model at locations where the team is interested in reading light levels. Computer simulations use digital sensor points instead. Sensor points can be placed anywhere in 3D space or on a horizontal, vertical grid. They are placed in specific locations to answer the underlying questions—recording temperature, airflow, light levels, or any nearly other quantity. They often graphically display results using false colors.

False colors are used in many analyses to graphically convey levels of solar energy, light, heat, or other results. The range of false colors span from a minimum to a maximum quantity, showing the results graded across space or time. The upper and lower thresholds are often automatically set by the software, but the user needs to check the range provided before interpreting the results. All false color results in the same presentation will generally be set to the same scale so the results can be read consistently.

SCALE AND COMPLEXITY

There are generally three scales of analyzing building performance. The appropriate scale is determined by the framing of the question and the level of detail required for the answer.

Single-aspect analysis evaluates a design for a single influence—solar irradiation, daylight, glare, airflow, or others. This type of analysis is powerful because it is very quick and accurate. For example, when designing a shading device to minimize direct solar gain in late August afternoons, an entire solar irradiation analysis can be set up and performed in half an hour; or three skylight options can be tested for their approximate reduction of electric lighting use in a simple classroom in an hour at the early design stages. Designers can often intuitively account for the absent inputs.

Focusing on one aspect permits the software to be more accurate with regards to that aspect than broad analyses like shoebox and whole building energy simulation (WBES) analyses. For this reason, outputs from single-aspect analyses are often used as inputs to more comprehensive shoebox and WBES models. For the Bullitt Center, the project team generated electric lighting schedules using daylight analysis, that were then used to calibrate the WBES electric lighting schedule as described in Case Study 10.7.

A *whole building energy simulation* (WBES) considers nearly all energy-related aspects of an entire building, often taking two weeks or more to set up, calibrate, and present results back to the team.

2.7

While a whole building energy simulation estimates the performance for an entire building, representative floors are typically modeled, including the lowest (1), middle (2), and top floors (3) of a high-rise, with multipliers being used to account for the other floors. Each atypical floor is modeled separately. Shoebox modeling analyzes a single floor or space within a floor for energy performance. For instance, a corner of a building (4) that may be exposed to solar energy from multiple directions can be tested for comfort and energy performance. A shoebox model can also be used to estimate and improve the energy use of smaller or unique spaces (5). Any scale can be studied more quickly with a single-aspect analysis, including an entire building, a single floor, or unique condition.

Source: Photo of LEED Gold certified MixC Chengdu © 2012 Callison LLC.

A WBES results in a detailed account of a building's energy use and can be a powerful early design tool. Currently, however, geometric options are costly to study because each requires a new of significantly revised mechanical design. Despite the benefit, clients are often unwilling to spend the money to get early feedback from a WBES, and it ends up being run once or twice towards the end of a project as a compliance tool for energy codes and LEED points. However, many architectural and engineering firms are working to reduce the cost of WBES so it can be used more easily in early design. For example, LMN Architects worked with Arup on a system to automatically export geometry and glazed areas from the architectural design model in Rhino to the engineer's energy model.

Shoebox analyses include a breadth of scope similar to a WBES, but often use averaged data to account for mechanical systems. They use boundary conditions to limit the geometric size and simulation scope. To define the boundaries of a shoebox simulation, imaginary walls through which no energy passes (adiabatic) are used so that the analysis can focus on the few façades through which most heat transfer will occur.

Shoebox models are usually automated, meaning that the hundreds of inputs include reasonable defaults settings. The defaults generally use a mix of national average data and more specific data for each typology and climate. Good software lists the inputs and allows them to be changed, so an architect or engineer can go through these and customize aspects that are unique to the project.

For example, a shoebox model of a hotel room may have defaults for an industry-norm Lighting Power Density, Occupancy, HVAC system, etc. This allows an architect to model a specific hotel room's geometry and fenestration, place it in the correct climate at the correct orientation, and test design options. Since the corridor and common space conditions are not considered in this example, building-wide energy use cannot accurately be predicted, but the design options can be reasonably compared.

CONCLUSION

Architects' complete reliance on engineers and energy analysts has hurt our understanding of how building design affects energy use. With an integrated design team and current software, architects can begin to engage in design simulation, re-learning how to achieve performance through passive design. While most of the detailed modeling will be done by engineers, architects who learn to simulate can begin to understand and design for energy performance. They can also more easily communicate with engineers and energy analysts, resulting in a more integrated decision-making process that helps achieve low-energy goals.

3

Comfort and Controls

Man is the measure of all things.

—Protagoras

A shift is required from conceptualizing the occupant as a passive recipient of a set of indoor conditions, to the inhabitant, who may play a more active role in the maintenance and performance of their building.

—Cole and Brown, 2009

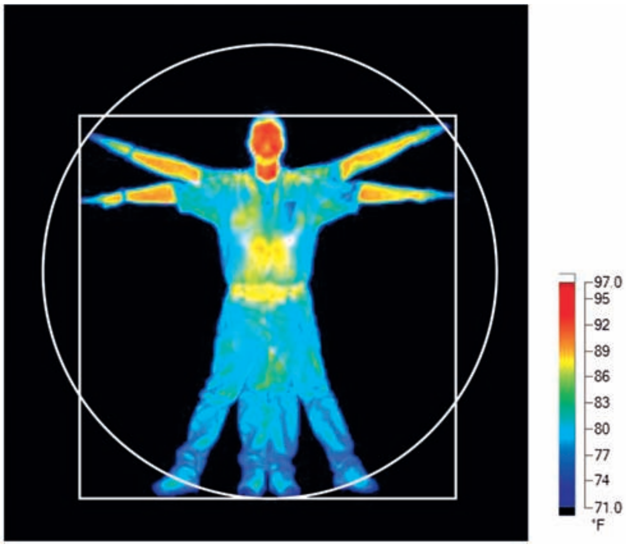
Buildings use a great deal of energy to provide comfortable environments for their occupants. We prefer certain ranges for temperature, humidity, oxygen, and light. Our idea of indoor thermal comfort changes as we adapt to changing outdoor temperatures through each year. We also have individual differences and preferences that make designing a "perfect" space for all occupants improbable. The definitions and descriptions of human comfort are used as the baseline against which building performance is evaluated.

As an example, discussions on the acceptable comfort zone were instrumental in reducing energy use and the initial cost of DPR Construction's offices in Newport Beach. Their previous Net Zero Energy offices had experimented with the maximum interior temperature, finding that 83°F or more did not evoke complaints when large, overhead fans provided air movement. First-hand experiences with an expanded comfort zone, plus additional research, allowed the team to reduce the number of operable windows retrofitted into their Newport Beach offices for natural ventilation, saving capital costs and reducing the amount of time the mechanical system is used. See Case Studies 9.4 and 10.6.

As a negative example, a daycare project that achieved a high LEED rating used significantly more energy than projected. During the Value Engineering process, the team substituted airflow vents for natural ventilation, while also providing sapling shade trees instead of horizontal shades per the design. The substituted vents did not close completely, so the occupants adapted by bringing in space heaters during winter. In addition to using more heating energy than expected, there were several days each summer when the trees did not provide enough shade and the internal temperatures were too high for the children's health.

If comfort is the absence of discomfort, it is well beyond the scope of this book to address all possible sources. The focus for this chapter is on thermal comfort. Air quality is important to human health and affects energy use, but is not covered here. Visual comfort will be covered in Chapter 8 on daylighting.

Providing comfort in low-energy buildings is one of today's environmental design challenges. In the recent past, a narrow range of indoor temperatures have been assured by over-sizing building systems by a factor of 2 or even 3, which reduced their operating efficiency. Right-sizing these systems, which reduces capital cost and operating energy use, requires a more thorough investigation of expected building operations, better energy modeling, and an understanding of human comfort conditions.



3.1 *(top left)*

Human comfort is the measure of building performance.

Source: Original thermal images courtesy of Phil Emory of Neudorfer Engineers.

3.2 *(top right)*

Thermal images showing surface temperatures of four people. The two in the middle have higher metabolic rates than the two on the edges.

Source: Courtesy of Phil Emory of Neudorfer Engineers.

HUMAN THERMAL BALANCE

While most people's preferred environmental temperatures are in the 70s (°F), our healthy, internal "core" temperature is 98.6°F. For this reason, we are generally net exporters of heat to our environment. Thermal comfort is therefore based on people's ability to shed the right amount of heat.

We dissipate heat to our environments through: (1) inhaling cooler air and exhaling warm, moist air; (2) radiating heat from exposed skin to surrounding surfaces; (3) air movement wicking heat from clothing and exposed skin, as well as evaporating sweat to provide evaporative cooling; and (4) conduction/radiation through our clothing and feet to surrounding surfaces and air currents. When these methods become less effective due to environmental conditions, we can overheat. For example, high humidity reduces the effectiveness of sweating, while a high air temperature can reduce the effectiveness of 1, 2, and 4. All of this dissipated heat from people becomes part of the building cooling energy load as described in Chapter 10.

We gain heat by burning calories, being in contact with a hot breeze or object (electric blanket or hot coffee), or being in the radiant path of a heat source such as the sun, a fire, or a hot radiator.

WHAT AFFECTS THERMAL COMFORT?

Thermal comfort, or dissipating the right amount of heat to our environment, depends on a balance between four factors controllable by building systems: air temperature, mean radiant temperature, air speed, and humidity. Two additional factors are based on the occupants themselves: metabolic rate and clothing insulation. The adaptive comfort model adds other factors: local outdoor temperature history and some aspects of psychology.

Most people associate thermal comfort with air temperature. Home thermostats cycle on and off based solely on air temperature, and furnaces supply warm air to adjust the air temperature. Studies show that human thermal comfort is actually more dependent on mean radiant temperature (MRT), which is only indirectly affected by warm or cold air supply. MRT is the average temperature of the surfaces around us, modified by their surface emissivity and our geometric location within a space. Many low-energy buildings use radiant heating and/or cooling, since it is a more effective (and efficient) method of providing comfort.

All surfaces constantly exchange "long-wave" radiant energy, heating up cooler ones and cooling warmer ones. We constantly send and receive radiant energy as well, and the perceived thermal comfort of a space is largely based on the quantity of radiant energy we receive. An auditorium, a party, or packed conference room can overheat quickly, partly due to people exchanging radiant temperatures with 90–95°F skin instead of with 65°F walls.

Air speed helps dissipate heat by removing a layer of air that heats up around us, and providing airflow that increases evaporative cooling through sweat. Airspeed is often controlled through natural ventilation, a mechanical airflow using fans within ductwork, or overhead fans.

The last factor controlled by building systems, humidity, is often tempered by a mechanical system. A heating system lowers the relative humidity of cooler outdoor air. Warm, humid outdoor air is usually cooled to 55°F, which drains moisture (called condensate) out of the air. This air is then brought into a space, mixing with warmer indoor air, lowering the space's relative humidity. It is interesting to note that, though humidifiers are common in cold climates, the ASHRAE 55 comfort standard has upper limits for humidity, but no lower limits.

Clothing insulation and the metabolic rate of occupants also affect an individual's comfort level. A typical level of clothing (measured in clo) is assigned to occupants: a clo of 0 is nude, while a clo of 1 includes a typical business suit. Metabolic rate (1 met = 18.4 Btu/h/ft^2, where ft^2 refers to a person's total skin area) is based on the activity level of the occupants. In an office, people are assumed to be fairly sedentary (met = 1.0–1.2) with pants, a shirt, and sometimes a jacket (clo = 0.8–1). In a gym, people will be fairly active (met = 2–7 or more) and wearing shorts or sweats and short-sleeved shirts (clo = 0.3–0.6). In some typologies such as swimming pools, spas, and on-mountain ski retail, people can be assumed to wear significantly less or more clothing.

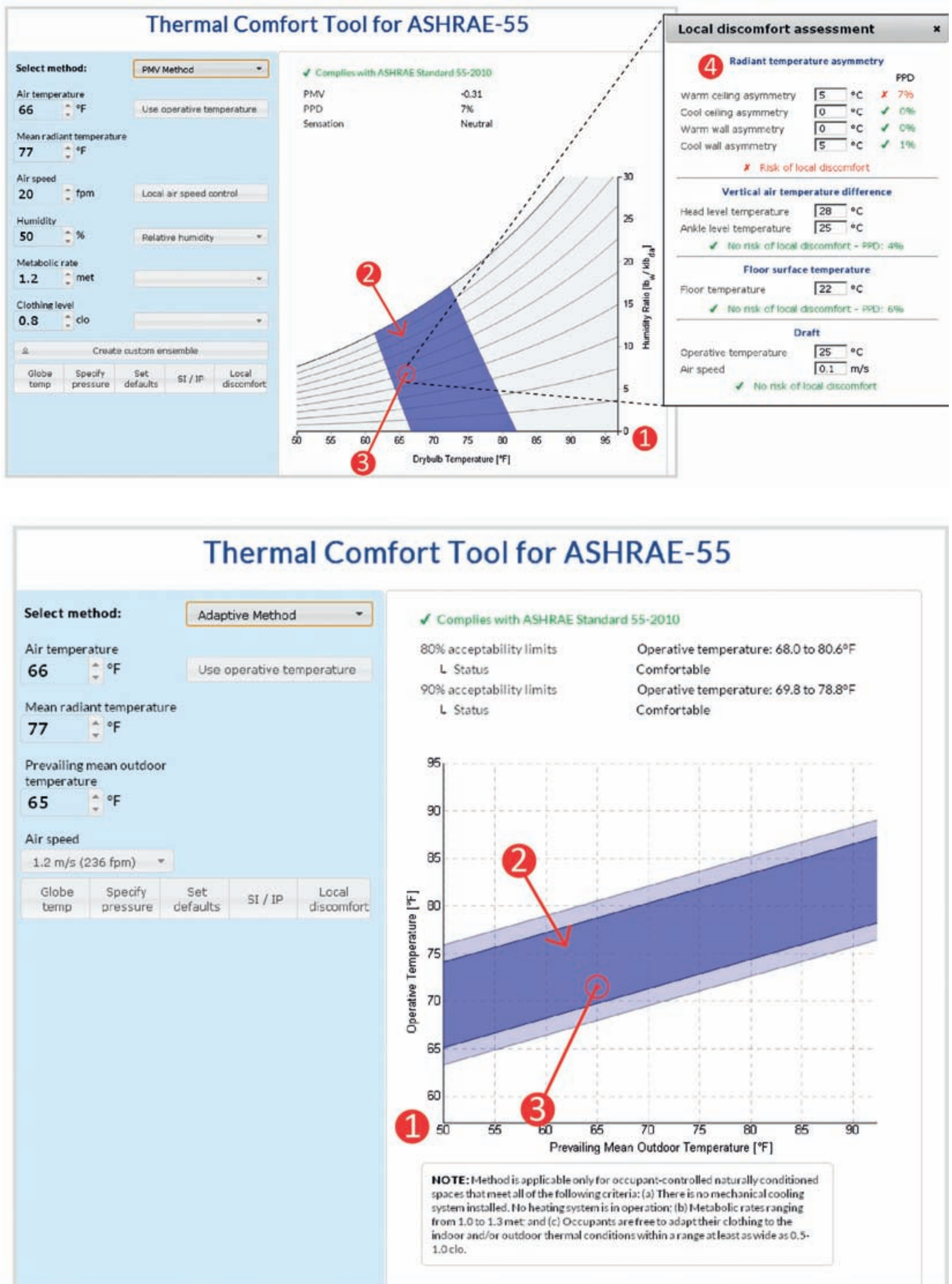
The science is much more detailed than presented here, including clothing permeability and layering, convection based on body position and exposure, and heat loss through each portion of the body. The *ASHRAE Handbook of Fundamentals* (ASHRAE, 2013) contains dozens of equations that help estimate heat transfer through clothing and metabolic rates. These equations, however, are often directly included in simulation software that reports thermal comfort, while simulation software that reports energy use is guided by one of the methods described below.

DEFINING THERMAL COMFORT RANGES

Human comfort is a soft science, relying on individuals self-reporting their satisfaction with their environmental conditions. Subjects are exposed to various combinations of air temperature, humidity, air speed, and MRT, and their responses reflect these environmental factors, plus psychology, age, culture, and thermal expectations. Due to individual differences, ASHRAE standards expect that 10–20% of the occupants of a given space may not be thermally comfortable, even in a well-designed building. Occupant controls increase thermal satisfaction, and will be discussed later in the chapter.

The two main definitions of thermal comfort, static and adaptive, are based on lengthy and detailed studies of individuals self-reporting comfort. Most of the studies ask occupants to rate their thermal sensations on a scale from –3 (cold) to +3 (hot), with 0 being thermally indifferent.

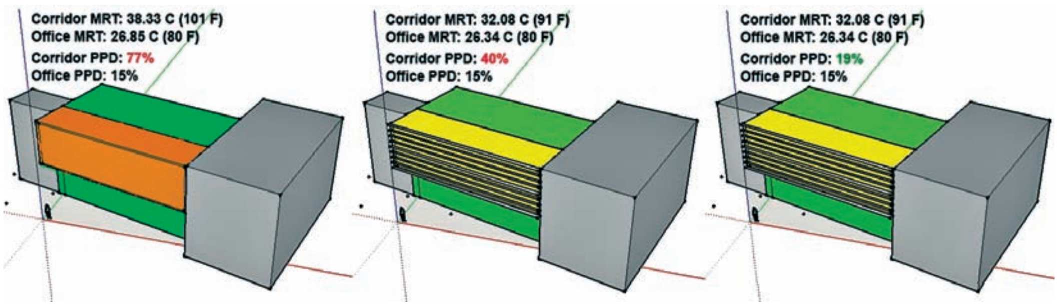
A space is considered to be adequately comfortable if the calculated mean thermal sensation response (the Predicted Mean Vote or PMV) is between –.5 and +.5. This range of PMV has been found in field studies to satisfy 80% of the average population. Due to individual preferences and differences and natural temperature fluctuations, achieving 100% PMV is not considered possible in a uniform environment.



3.3

A real-time, interactive comfort tool for indoor conditions based on ASHRAE-55–2010 from the University of California, Berkeley, can be used to understand the ranges for the Static (Predicted Mean Vote) and Adaptive comfort models. Note the different X and Y axis labels (1). The comfort zone (2) is plotted in purple. For the Static model, this area changes based on met and clo values, while the dot (3) shows whether a specific combination of environmental factors is predicted to result in thermal comfort. In the adaptive model, the comfort zone changes based only on air speed, while the dot (3) changes position, based on air temperature, air speed, and prevailing mean outdoor temperature, calculated based on the last week or more of outdoor temperatures. Asymmetrical discomfort (4) may occur due to a warm ceiling and cool floor.

Source: CBE Thermal Comfort Tool for ASHRAE-55, http://www.cbe.berkeley.edu/comforttool/.



3.4

Within a highly glazed corridor, the addition of blinds and an increase in the airflow can be seen to reduce discomfort. False colors are used to show the temperature of the corridor. The unshaded façade on the left can overheat beyond the capacity of a mechanical system to create comfort. Instead, the addition of horizontal shades were necessary to reduce discomfort, with increased airflow being necessary as well to reduce Percentage People Dissatisfied (PPD) below 20%, a common upper limit.

Source: Open Studio thermal comfort model, courtesy of Premnath Sundharam.

While studies control for the environmental factors covered in the previous section, there are many psychological and environmental factors that may influence self-reported thermal comfort that are not captured in the studies.

People's range of comfortable conditions changes throughout the year. An individual may be comfortable in shorts on a 60°F sunny day in the Spring, while on a 60°F sunny Fall day they may choose to wear a coat. The Static model in ASHRAE 55 defines Summer and Winter comfort ranges using temperature, humidity, air speed, and mean radiant temperature. Many studies have proved that mechanical systems operated within this range will consistently satisfy more than 80% of occupants, an industry benchmark for comfort.

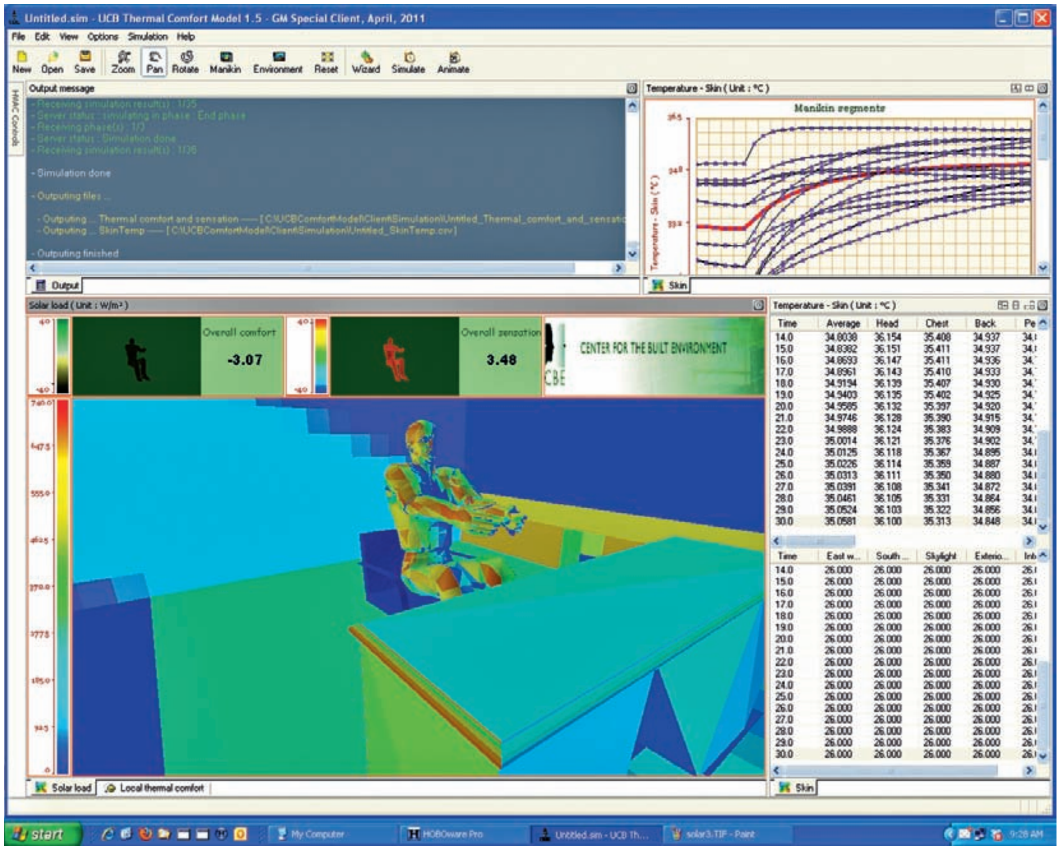
The Adaptive model asserts that people's idea of comfort changes daily and weekly, especially in relation to recent, local outdoor temperatures. This is known as acclimatization. The degree to which an environment meets expectations, or is adaptable by the user, also plays a role. Instead of passively accepting a narrow range of acceptable temperatures, this model assumes the occupants will add or remove clothing to maintain their comfort within a slightly wider range of temperatures. The Adaptive model is especially effective for predicting comfort within naturally ventilated spaces.

Interpretations of the ASHRAE RP-884 database of naturally ventilated buildings show that occupants in naturally ventilated buildings prefer a wider range of temperatures than predicted in the Static model (Brager and de Dear, 2001), related to outdoor temperatures among other factors. Occupants of mechanically conditioned buildings also were shown to prefer the narrower range of comfort conditions which they were used to, hinting at the roles played by psychology and acclimatization in thermal comfort.

The Adaptive model is becoming more widely accepted, but needs more rigorous field studies to assess impacts. ASHRAE's Standard 55 for human comfort added an adaptive option in 2010. This allows the comfort design parameters to include recent outdoor temperatures.

The criteria of thermal comfort used on a given project can have major implications. When a project team is confident that a space can be 3°F higher during the summer, they can reduce the mechanical equipment size and first cost. Expanded comfort criteria, especially along with good shading and lighting design, can allow more efficient systems to be used, such as radiant cooling or natural ventilation, see case study 7.1.

First-hand experience with comfort ranges can be essential in determining if a client is willing to accept a wider comfort range. In Oregon's BEST labs, a comfort chamber has been built where all four PMV factors can be tightly controlled to find comfortable ranges. Radiant wall panels can be quickly adjusted to a new temperature, airflow, air temperature and humidity can also be controlled. Skeptical individuals are allowed to hold meetings in the comfort chambers, periodically reporting their comfort level. When they are finished, the combinations they reported as comfortable often surprise them.



3.5

The Berkeley Comfort Model software simulation shows a person sitting near a window with sunlight coming in from the left. The software simulates solar transmission through the glass, as well as all long-wave radiation exchanges with windows and walls, local temperatures, humidities, and air movements surrounding the body, and the person's clothing and activity levels. These contribute to the skin temperatures of the body (shown in false colors) which in turn contribute to the person's thermal sensations and comfort. Due to the strength of the solar radiation, there is local discomfort on some body parts that override the comfort on other parts, producing an overall comfort of -3.07, which rates as uncomfortable on a scale from -4 (very uncomfortable) to +4 (very comfortable), with 0 as the minimum threshold for comfort. The software is used by auto-makers, engineers, and other industries to predict human comfort.

Source: Image courtesy of the Center for the Built Environment.

COOL HEAD, WARM FEET: ASYMMETRICAL DISCOMFORT

The previous section assumed that a space was at a uniform temperature. Mean radiant temperatures may vary significantly near exterior walls, especially near highly glazed façades, causing asymmetrical discomfort.

Instead of assuming the body loses heat consistently across the entire surface, people shed heat asymmetrically. Hands and feet normally vary within a 10°F range but our core temperature varies less than 1°F in a healthy person. Studies conducted by the Center for the Built Environment at UC Berkeley model temperatures over 16 parts of the body—arms, legs, head, and others, with each receiving unique temperature signals. Discomfort can be predicted if some parts are significantly warmer than others.

For example, if the left side of the body faces a cold window, enough radiant heat may be lost to the window that, even though the four comfort criteria described above are met, an individual reports being uncomfortable. Super-insulated buildings and those with thermal mass tend to have more consistent MRT and air temperatures, even near windows, and thus have reduced potential for asymmetrical discomfort.

OTHER INDOOR COMFORT FACTORS

Visual discomfort, or glare, can quickly turn a well-daylit space into one with blinds drawn and artificial lighting on. In addition to contrast glare, visual comfort is affected by the color temperature of the lighting, the specularity of surfaces, the balance of lighting levels within the field of vision, and other factors. Visual comfort is covered in more detail in Chapter 8 on daylighting.

Air quality also affects indoor comfort. Before buildings were well sealed, air flow through the envelope generally dissipated mold, spores, volatile organic compounds (VOCs), dust, and other airborne particles. In tighter buildings with more chemical-laden indoor furnishings, poor air quality results from not cycling enough fresh air through a space, which can increase sick days, asthma, and many other maladies. A study of asthmatic children found that transitioning their families to homes with good air quality reduced emergency room trips by 66% (*A New Prescription*).

CONTROLS: AUTOMATED, MANUAL, AND INTERACTIVE

Building control systems are becoming more sophisticated, an play an integrated role in nearly every aspect of building performance, though not without their problems. Excluding installation and maintenance, problems are often a result of the design team not considering the character and extent to which building occupants will be engaged in the energy performance of their building.

Automatic controls are tied into a building management system (BMS) to operate heating and cooling systems, blinds and shades, electric light dimming, operable windows and trickle vents, fans, and others. A BMS can also monitor roof sensors for wind, solar energy, and temperature, as well as read occupancy sensors and photosensors to aid in predicting heating and cooling loads and controlling the systems.

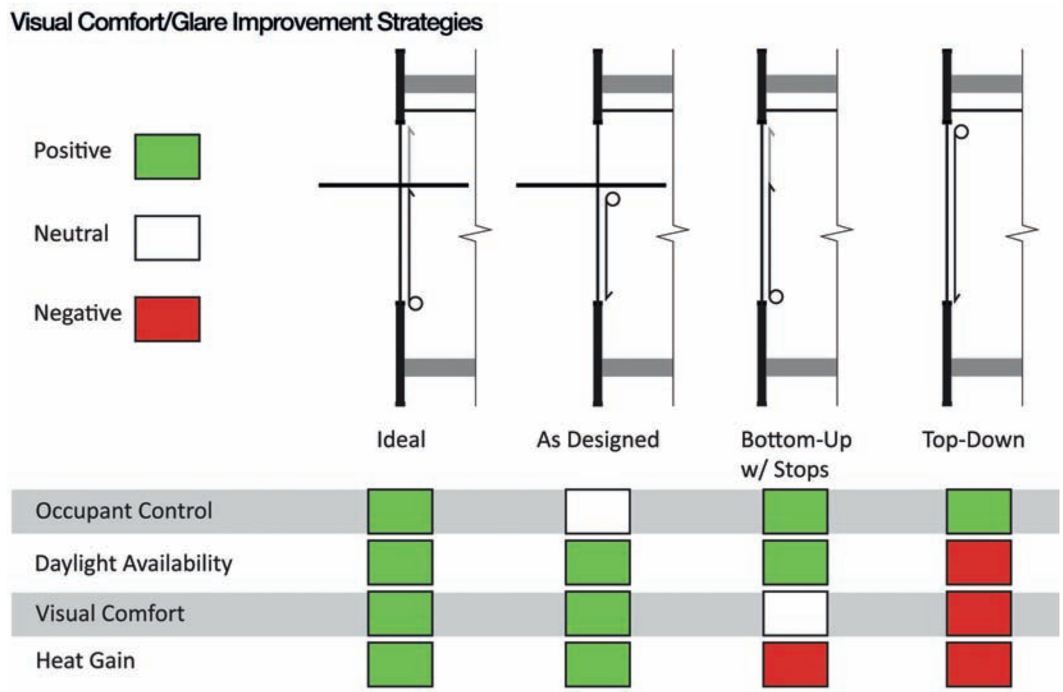
Automatic controls require the set-up and maintenance by a sophisticated user. In most buildings under 50,000ft^2 there is no dedicated facilities manager, so the programming and repair of automated components are often neglected. For larger projects, mechanical engineers generate sequences of operations for automatic controls. The contractor needs to determine how to wire it, provide actuators for moving parts (such as blinds, operable shading, automatic windows), and locate photosensors and CO_2 sensors, while the facilities manager needs to incorporate weather forecasts and on-site weather stations, and tie all of them into the BMS software. When these are not complete to exactly match the design intent and assumptions, the theoretical energy savings from the energy model do not materialize.

The author helped design a small building where expensive, sophisticated, automatic controls (with large theoretical energy savings) resulted in lighting that automatically turned off every day at 5 p.m. The staff member who was briefly trained to program the system was not able to recall the training,

3.6

A study prepared for Iowa State University by ZGF Architects LLP rates four window options for user controllability, daylight availability, visual comfort, and heat gain. While simulations predict lighting energy savings due to the use of daylight, these savings are only realized when the system successfully blocks glare or allows users to block glare without blocking daylight.

Source: Courtesy of ZGF Architects LLP.



meaning that someone had to be stationed near the lights during meetings that ran past 5 p.m. to immediately turn the lights back on.

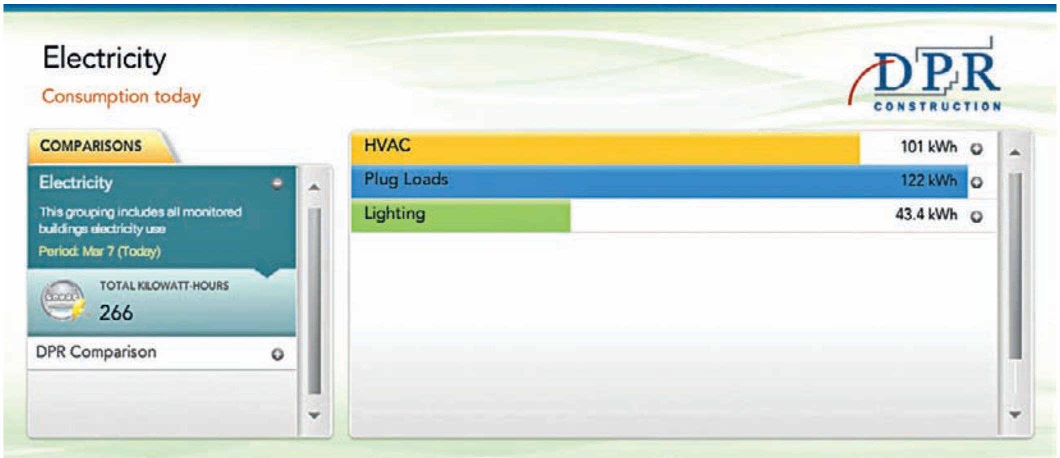
Automatic controls can result in large theoretical energy savings, often assuming that individuals are passive recipients of comfort. However, occupants generally want some control over the spaces where they spend long periods of time, such as offices, homes, hotel rooms, and hospital patient rooms. Often occupants will try to override automatic blinds to maximize their view or reduce the glare, block air vents to reduce unwanted cool air or high air speeds, or purchase space heaters in an attempt to create comfort conditions.

Studies looking at the adaptive thermal comfort model have found that people self-report higher levels of comfort when they have some control over their thermal environment. Local temperature or air flow controls, operable windows, operable blinds, and other mechanisms cede some control to occupants, with higher theoretical comfort levels.

Manual controls are not foolproof, either. They need to be located in logical places, often adjacent to the system they control for ease of use or else may be ignored. On a sunny afternoon when the majority of the occupants are away, operable windows may not be opened if they are manual, resulting in increased HVAC cooling instead of natural ventilation. Manual blinds closed to block a few minutes of glare often end up blocking light and potentially desirable solar heat all day. Automated systems would retract neglected blinds when the right outdoor conditions are present.

When determining whether manual and automatic controls are to be used, the architect is encouraged to understand and graphically present how occupants are likely to use each space—daily and seasonally—to mitigate glare, control thermal comfort, and enjoy views.

As part of this effort, the information and controls available to occupants can be important. Similar to cars that display a driver's current fuel efficiency, a dashboard that shows building occupants their current energy use can create a culture that is more aware and proactive about turning off lights, operating blinds, and opening windows for natural ventilation. Locating a dashboard on each person's computer or tablet can alert people, similar to the alert when an email arrives, that interaction with their environment may be required.



3.7 and 3.8

Great design strategies are more effective when energy use becomes part of everyday consciousness, conversation, and action by those who occupy the building. An online, real-time energy use tracker is a way of engaging occupants in building operation using software deployed to workstations, tablets, and phones. The dashboard for DPR Construction's Newport Beach office tracks building energy use against goals, past performance, and other metrics.

Source: Courtesy of Lucid and DPR Construction.

Chapter 10 discusses how user and automatic controls and user assumptions can become part of energy models. A simple shoebox model can help estimate the effects of controls on energy use. For a retail design in Phoenix, four different interior blind control assumptions led to a 5% difference in PMV and an 11% difference in energy use.

CONCLUSION

Many energy use decisions are made with reference to providing human comfort. As the case studies throughout this book show, low-energy design also requires a consideration of how occupants can control their environment, and supplying them with the right information and controls helps them ensure their own comfort with little energy use. An architect cannot expect building users will understand how all the building systems interact in low-energy buildings, so a balance must be struck between using automated and manual controls with simple user engagement.

4

Climate Analysis

Climate is what we expect, weather is what we get.

—Mark Twain

Our climates used to define us—available food, typical clothing, seasonal customs, and vernacular architecture all responded directly to challenges and opportunities posed by each climate. A photograph of a modern building gives nearly no indication of its climate—shading, orientation, massing, or otherwise. Low-energy buildings often opt for regionally appropriate characteristics, which may be significantly different from historical vernacular. They are often asymmetrical due to weather conditions and sun angles.

We are beyond the brief period when coal and oil energy shielded us, seemingly without consequence, from designing for climate. Most citizens accept that fossil fuel energy is the major contributor to global climate change. We also know that shielding ourselves completely from nature is not even desirable: biophilic human interactions with daylight, views, vegetation, and seasonal changes have positive health and productivity benefits.

Just as most building energy questions are rooted in creating human comfort, the creation of comfort is based on how buildings interact with ever-changing outdoor conditions. Each case study in this book illustrates how architects have used climate data within simulations to determine or validate appropriate climate responses.

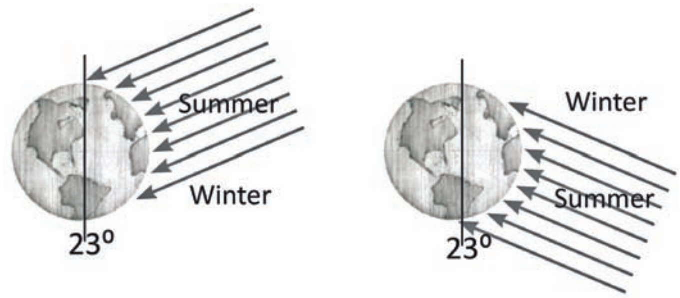
Many sustainable design resources recommend strategies based on climate classification, which serves as a starting point for design. Since climate classifications are necessarily general, each potential strategy needs to be validated within a micro-climate with experience or simulation. To evaluate climate-responsive design with software, practitioners need to understand how temperature, humidity, wind, solar irradiation, and other factors can influence building design. They need to understand how weather is recorded and used in building simulations, and how location-specific factors make a micro-climate unique from the nearest weather data.

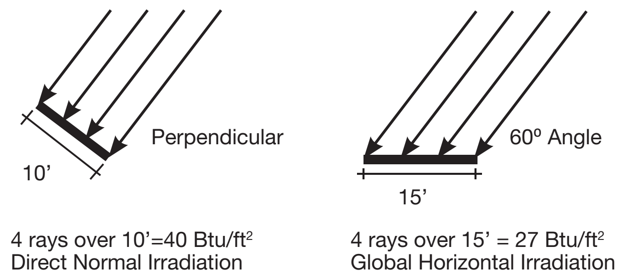
THE INTERACTIONS THAT CREATE WEATHER

Our sun and its constantly changing relationship to the Earth generate nearly all climatic conditions on Earth. What we refer to as weather are the effects of global patterns on the thin layer we inhabit near the Earth's surface.

Our sun emits energy (light and heat) as short-wave radiation. Around 435 Btu/h/ft^2 is received by the upper atmosphere. Sunlight is scattered by molecules and dust particles and absorbed by ozone, mixed gases and water vapor, including clouds and smog; a maximum of around 320 Btu/h/ft^2 actually reaches the Earth's surface. Sunshine scattered by the atmosphere becomes a source of ambient light and heat.

The angle between the sun's rays and the ground determines the density of energy striking the Earth's surface. Sunshine perpendicular to its surface delivers much more energy per unit area than at





4.1 and 4.2

The angle at which the sun's rays strike the Earth determines the overall heat absorbed. The higher and lower sun angles are the major drivers in creating seasons.

Source: Amal Kissoondyal.

any other angle. Low winter sun angles, combined with fewer total hours of solar irradiation, result in significantly less energy delivered during winter. This principle, plus some atmospheric effects, results in seasons.

CLIMATE DATA

Climate data is much more local, accurate, and available than it was a few decades ago. Charts of solar angles, sun path diagrams, and generalized climate types have given way to city-specific climate data collected at airports that can be graphed or used as an input into design simulations.

There are many ways to visualize the data, and each sustainable strategy requires the study of a unique combination of climate data inputs. Some methods of looking at the data are included in this chapter, but the reader is encouraged to learn to convey climate information to produce outputs unique to the building design and strategies being considered.

There are generally two ways that climate data is packaged for use in building simulations: (1) annual weather files, which contain data for each of the 8760 hours in a typical year; and (2) peak condition files. Annual weather files are used to produce annual energy use simulations, such as Energy Use Intensity (EUI) studies. Peak condition files are used to help simulate how comfort may be created under a climate's most extreme conditions. Simulations using peak data are used to select and size mechanical systems, a major consideration in a project's first and life-cycle costs.

A weather file includes climate data plus information about the weather station such as: latitude and longitude, time zone and daylight savings observance, altitude above sea level, and other site information. The solar path is not recorded in weather files since software can instantly calculate it based on latitude and longitude. In addition, it usually records the following metrics at least once each hour:

Air temperature (dry bulb)	Wind direction and speed
Dew point temperature	Relative humidity
Wet bulb temperature	Absolute humidity
Global horizontal radiation	Cloud cover
Diffuse horizontal radiation	Rainfall
Direct beam radiation	Illumination levels

ANNUAL DATA SETS

Annual data sets often include hourly measurements of the above variables, so each day has 24 entries for each variable and each year has 8760 entries. Modern annual weather data used for annual design simulation began with Typical Meteorological Year (TMY) data and was refined for TMY2 (1961–1990) and TMY3 (1991–2005) data sets. In the USA, the Sandia method (named for the Sandia National Labs) uses algorithms to select the most typical hourly weather readings in January from the measured data

4.3

While weather data is typically collected at airports, wind data for natural ventilation simulations is best informed by local data. A weather station was located across the street from the Net Zero Energy Bullitt Center to provide site-specific weather data that can be used to calibrate city-specific data.

set based on five weighted factors. Other months are similarly selected to produce a synthetic "typical" year, and then the months are smoothed so that they join together to form a full year. Whole building energy simulations, all of the graphic climate information in this book and nearly all of the case studies use freely available TMY2 or TMY3 files. More information can be found in the *Users Manual for TMY3 Data Sets* (Wilcox and Marion, 2008).

This annual weather data has been translated into the popular EnergyPlus Weather (.epw) file format, available on the US Energy Efficiency and Renewable Energy (EERE) website. Thousands of TMY2 and TMY3 files are available for free download, covering most of the world's large cities (see http://www.nrel.gov/docs/fy08osti/43156.pdf, for TMY3 files). More information about the files and weather collection sources are available on that website. Private companies, such as Weather Analytics, also sell hourly weather files in standard formats if one is not freely available.

Actual Meteorological Year (AMY) files contain one specific year of data. This can be useful to compare the predicted performance of a building to actual performance, correcting for actual weather conditions in a given year instead of averaged TMY files.

For projects with enough time, a weather station can be located on site to get hyper-local data for one or more years to collect raw data. This can be especially important for wind data in urban or hilly regions.

There are now hundreds of thousands of weather stations around the world collecting raw, micro-climate data, though in many cases the data has not been verified or interpreted. Weather stations can cost between hundreds and tens of thousands of US dollars, plus the labor of extracting and interpreting the raw data. Installing the station requires guidance, as a nearby glass façade, for example, can affect the measured solar radiation (by reflection) and wind velocity (by blocking or re-directing). Parsing the raw data to generate a useful weather file can also be a challenge. Airport stations usually have no obstructions nearby to skew the data.

4.4

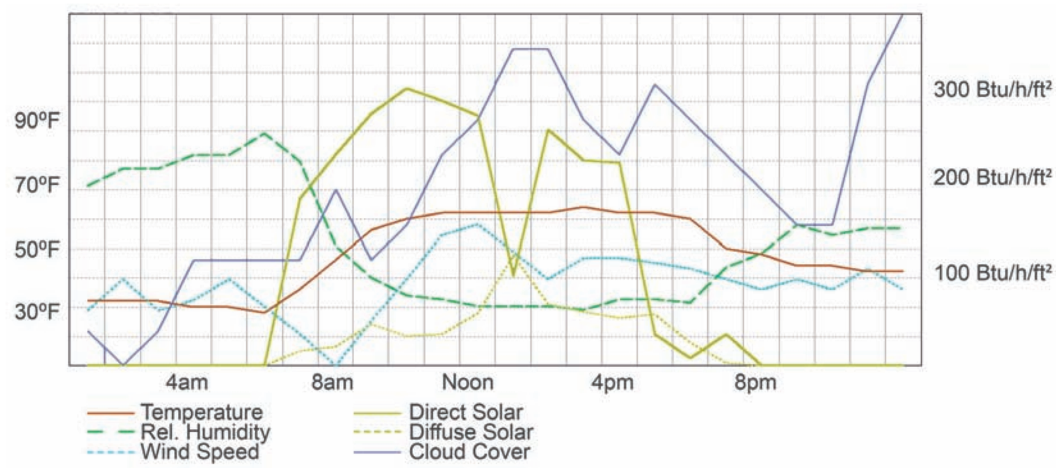
A weather data layer for Google Earth on the US EERE weather file site shows EnergyPlus weather file locations. This allows a designer to compare nearby weather files for the best site match, accounting for any change in elevation, proximity to mountains or water bodies, as shown in Case Study 5.3. Google Earth images use data from SIO, NOAA, the U.S. Navy, NGA, GEBCO, Cnes SpotImage, Terrametrics, and IBCAO.

On-site weather stations or other local, raw data generally spans only a few years and does not represent the long-term weather patterns, so it will not give reliable results for annual energy use simulations. However, this data can be useful. As an example, for a naturally ventilated building in Bothell, WA, LMN Architects wanted to know what the climatic differences were between the site and the nearest TMY data (Boeing Field) that would be used to run the annual energy model. If Bothell was typically several degrees warmer than Boeing Field on the hottest days, natural ventilation would be very difficult. Discontinuous weather data recorded on-site in Bothell was compared to AMY data from Boeing Field recorded over the same period. For the hottest group of days, temperatures were found to be nearly equal, with the main difference being higher diurnal swing and higher nighttime relative humidity in Bothell. Both of these were attributed to the adjacency of wetlands to the Bothell weather station.

To anticipate a changing climate, some organizations (such as the University of Exeter) have produced peer-reviewed "future" climate files, including multiple climate change scenarios.

As a caveat, annual weather files include average conditions while weather differs every year. For example, El Niño and La Niña years experience warmer and cooler ocean temperatures (respectively) in the Pacific, with global consequences. El Niño is associated with wetter winters and floods, as well as changes in wind patterns, lasting 12–18 months and occurring every 3–4 years. Ski resort operators, farmers, and power companies understand these yearly weather deviations, since they affect their businesses.

A robust design will reduce energy in nearly all years, even those that are fairly different from the design weather file. Buildings designed to be Net Zero Energy using average weather files will be Net Zero on average, but not necessarily in every year. As an example, the first year of operation of the Bertschi School in Seattle (Living Building Challenge Certified, including Net Zero Energy) included a winter that was colder and darker than the TMY data used in the energy model. This led to an increased



4.5

A 24-hour period set of data from a weather file shows the interaction of the dry bulb temperature, the relative humidity, the direct solar, diffuse solar, wind speed and cloud cover. Note the inverse relationship of temperature and humidity; direct and diffuse solar irradiation; and the inconsistent relationship between cloud cover and direct solar.

Source: Autodesk Ecotect Suite output of EnergyPlus weather data. Courtesy of Callison.

heating requirement and decreased photovoltaic production. The second year of operation, a more normal year, allowed the building to achieve Net Zero Energy.

PEAK DATA SETS

Mechanical systems are sized to create comfortable conditions under peak loads, which convey the most extreme conditions regularly seen within a climate. Peak loads have traditionally been calculated using design day (.ddy) sets of outdoor conditions found in the climatic design data in the *ASHRAE Handbook* (ASHRAE, 2013). This data on the hottest and coldest conditions has been copied into .ddy files that are downloaded from the EERE website alongside annual .epw files.

A system designed to meet the "99.6% design day peak heating conditions," for example, will maintain comfort conditions for 99.6% of the hours each year in terms of heating load. The remaining 0.4% (35 hours each year) can be met by oversizing the system or due to occupants' expanded comfort range based on recent outdoor temperatures, though this is not specifically addressed in the static model. A system designed to meet the same standard for cooling uses "0.4% design day cooling conditions."

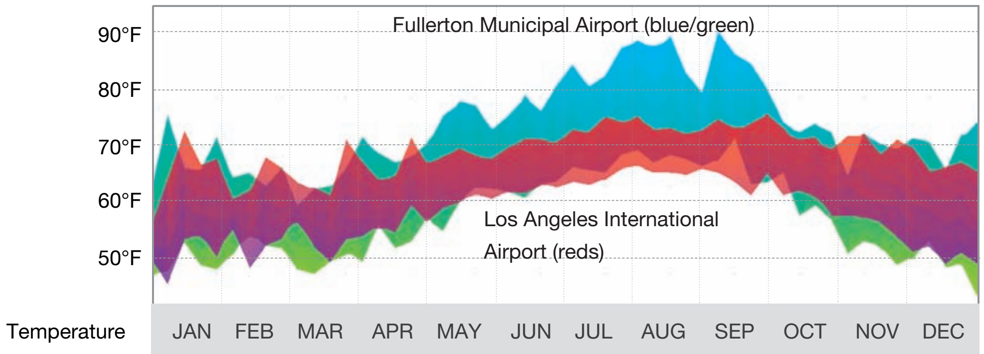
Each peak heating and cooling condition is assigned a specific day so the sun's path can be calculated. Files also include a sky clearness from 0 to 1.1, with 0 being overcast and 1.0 being sunny. Design day files contain multiple types of peak heating and cooling scenarios, which can be opened in a text file for inspection.

Since only one type of peak data set is constructed for each climate, this information can be too generic for low-energy buildings. For example, the Edith Green–Wendell Wyatt project team used March 15th as the peak cooling day for analysis of the south façade, due to the low sun angle. Each façade was assigned a different peak cooling day, see Case Study 7.1.

TEMPERATURE

Air temperature is the most commonly understood factor in thermal comfort, central to any weather report. Technically it is referred to as *dry-bulb temperature*, and is measured when a thermometer is shielded from solar radiation and dampness. A *wet-bulb temperature* is recorded by a sling psychrometer, essentially a thermometer with a damp cloth over it that is moved through the air. As the dampness evaporates, it reduces the temperature reading. At the temperature where relative humidity reaches 100%, also called the dew point, wet-bulb and dry-bulb measurements are equal.

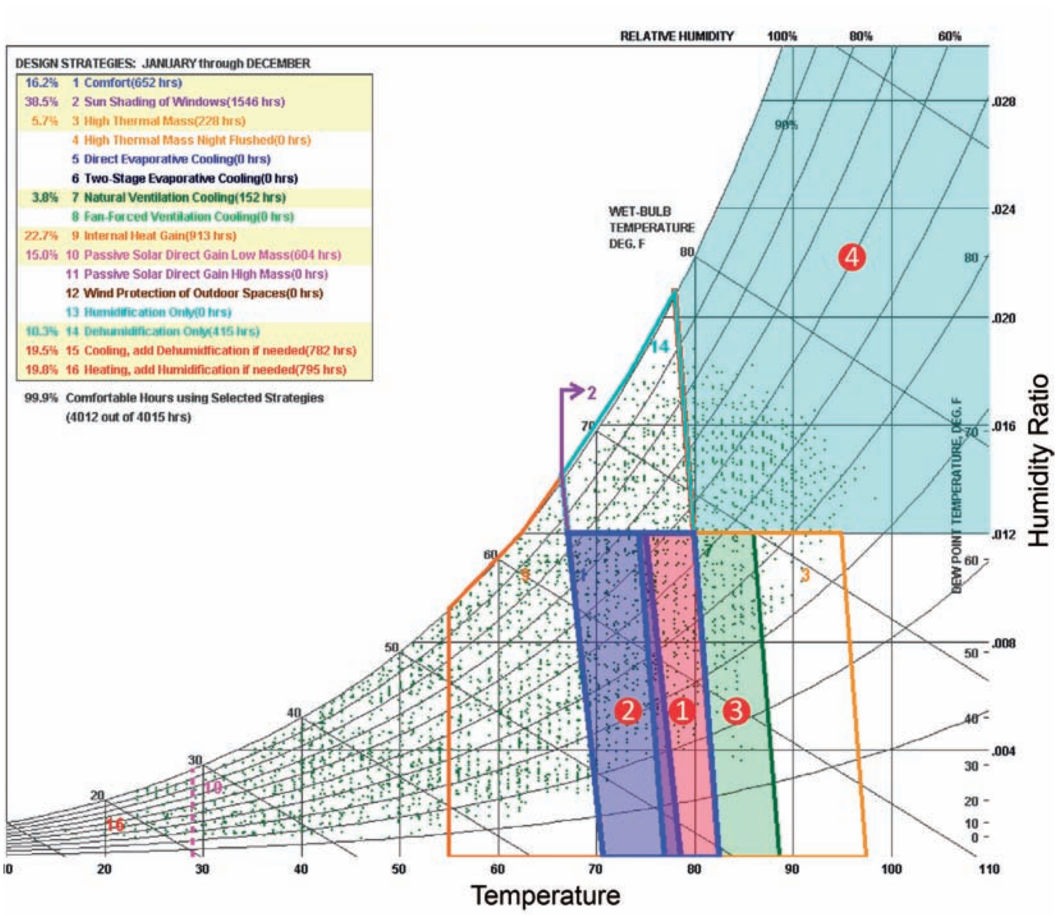
While not part of weather files, Heating Degree Days (HDD) are a general measure of the quantity of heating required for a climate. Each degree that the average daily temperature is below the threshold



4.6

Comparison of annual average temperature profiles from Los Angeles International Airport (LAX) weather station, 2 miles from the Pacific Ocean, and Fullerton Municipal Airport, 11 miles inland. Fullerton gets much hotter in summer than LAX and has a wider diurnal swing. This is due to being farther from the coast, resulting in lower humidity, proximity to the LA's urban heat island effect, and other factors.

Source: Courtesy of Callison.



4.7

Climate Consultant output of a psychrometric chart with interactive sustainable strategies. The chart shows temperatures along the horizontal axis and humidity along the vertical axis. Each hour of the year within the occupied time (8 a.m.–6 p.m. for this office project) is plotted for temperature and humidity with a green dot. Each hour where the combination of temperature and humidity naturally provide comfort are enclosed by the Summer (1) and Winter (2) comfort zones. Strategies that can provide comfort are listed in the upper left; each one encloses additional area of the chart, showing that it will provide comfort under those conditions. For example, Natural Ventilation (3) encloses those areas that are up to 6ºF warmer than the comfort zone, but not more humid. According to the tool, Natural ventilation will work 3.8% of the occupied hours. Hours that are both too hot and too humid require mechanical cooling (4); based on the strategies selected, 19.5% of the annual hours require mechanical cooling.

Source: Courtesy of UCLA Energy Design Tools Group, http://www.energy-design-tools.aud.ucla.edu/.

(HDD65 uses 65°F) counts towards the total. For example, if the average temperature on November 17th is 30°F 35, (65° minus 30°) is added to the monthly or yearly HDD65 total. Days with average temperature above the threshold are not counted. Cooling Degree Days are calculated in relation to a baseline the same way. New York City has a 30-year average of 4780 HDD65 and 1140 CDD65, while Atlanta's average is 3100 HDD65 and 2060 CDD65. Standard measurements are often based on HDD65 or HDD60, but modern buildings with insulation do not require heating until outdoor temperatures reach 55°F or less. See Case Study 10.5.

Some ways that temperature is used in building design and simulation are:

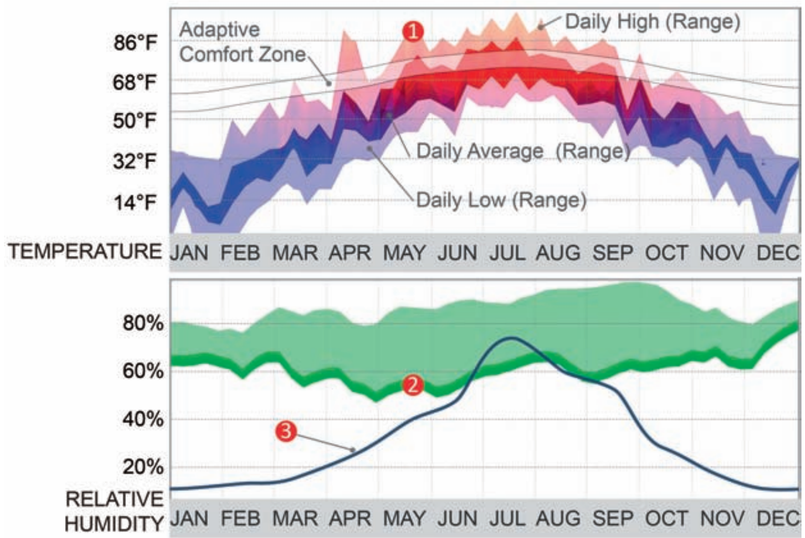
- Conduction loss or gain through the building envelope is based on the difference between the indoor and the outdoor temperatures, multiplied by the envelope's conductance, called the U-value. This is covered in Chapters 6 and 10.
- Prescriptive thermal insulation requirements are generally based on the number of heating degree days and cooling degree days.
- In cold climates, thermal bridges (such as a cantilevered concrete deck or a steel beam) can bring the outside temperatures in, increasing energy use and potentially condensing water from warmer interior air.
- People require fresh air to be brought into buildings to replenish oxygen levels and remove odors and pollutants; this air needs to be heated or cooled most of the time, requiring significant energy use in extreme climates.
- The Adaptive comfort model uses recent outside temperature history to anticipate the range of temperatures that people find comfortable indoors.
- Photovoltaics are less productive with high temperatures.

Micro-climate factors include:

- Topography, vegetation, colors and textures absorb and reflect the sun's heat in different ways.
- The urban heat island effect increases local temperatures, due to pavements storing solar energy, dark roofs absorbing heat during the day (reaching up to 160°F or more), and vehicle combustion and smog. According to modeling done in 1997 (*EPA Urban Heat Island*), Salt Lake City's urban heat island added around 7.2°F to night-time and 3.6°F to afternoon temperatures. The local peak power demand was increased by 85 mega-watts, with additional cooling costs due to the heat island effect around $3.6 million annually.
- Temperatures decrease 3–4°F for every 1000' of elevation gain.

HUMIDITY

High humidity in warm seasons is associated with increased discomfort, since it slows the body's ability to cool down through the evaporation of sweat.



4.8

Profile view of daily high temperatures (1) are simultaneous with low relative humidities (2), meaning that the bottom half of the humidity profile shows the expected peak daytime humidity. This information is useful for calculating thermal comfort with natural ventilation strategies. A line (3) shows the indoor relative humidity when outdoor air is heated to 70°. During most winter months the indoor relative humidity would be less than 20%.

Source: Modified Ecotect output of TMY3 weather file from Minneapolis-St. Paul International Airport. Courtesy of Callison.

Relative humidity (RH) is the most commonly used measurement of airborne water vapor, describing the percentage of water in the air to the maximum amount that the air can hold. Since warmer air can hold more water, a day's highest temperature usually corresponds with the lowest relative humidity. For example, an RH of 100% at 60°F in the morning warms to 80°F by noon, resulting in an RH of 50% even though the mass of water vapor (absolute humidity) per volume of air has not changed significantly. When 95% RH air at 80°F is cooled down to 65°F, it will shed water. Mechanical systems drain this water, called condensate, which can be measured in gallons per day even for small cooling systems in humid regions.

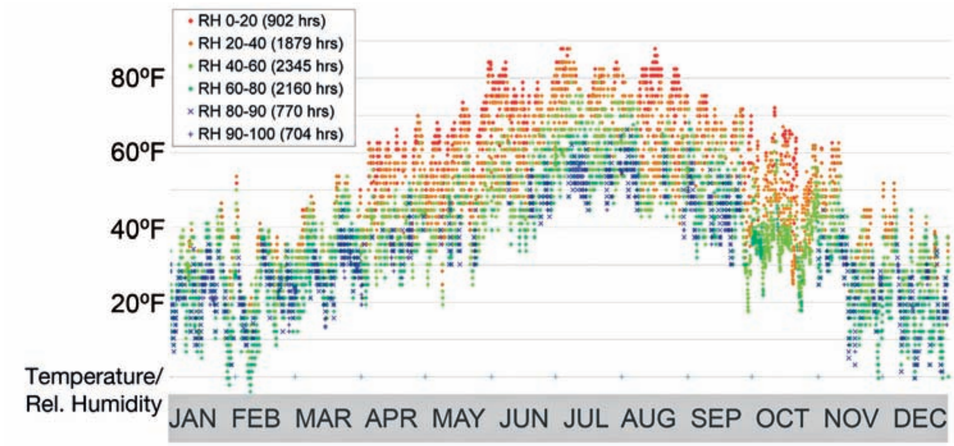
During cold seasons, outdoor air that is heated up to indoor temperatures often has a very low RH. For example, when 20°F, 90% RH outdoor air is heated up to 70°F, the RH drops to 13%. At low relative humidity, people's eyes and lips feel dry and static electricity is increased. For this reason, people in cold climates often use humidifiers.

Some ways that humidity is used in building design and simulation are:

- High humidity provides outdoor thermal storage due to water's specific density, limiting the temperature swing from day to night.
- The ASHRAE 55 Predicted Mean Vote (PMV) comfort standard specifies a maximum range of indoor humidity levels, but no minimum.
- People, showers, cooking, improperly covered dirt crawlspaces, and other factors add humidity to indoor environments.
- Evaporative coolers (swamp coolers) add humidity to outdoor air in arid climates to reduce the temperature, increasing comfort.
- The dew point is important in hygrothermic calculations, as it determines where water will condense within a wall or roof assembly.

Micro-climate factors include:

- Vegetation increases local humidity through evapotranspiration.
- Water bodies tend to moderate the nearby climate with humidity, and daytime breezes tend to head inland from the water body.



4.9

Temperature and relative humidity can be combined to show the relative humidity at each hour of the year, providing a quick look at peak summer natural ventilation potential. Peak temperatures in Vail, Colorado, reach above 80°F with relative humidity between 0–40%.

Source: Excel output of TMY3 data from Aspen-Pitkin Country Airport. Courtesy of ZGF Architects.

SOLAR RADIATION AND CLOUD COVER

Our sun has been a source of constant fascination throughout history as it gives us heat, light, provides energy for our food, and its absence, until recently, ended the workday. While it follows a daily and annual path, the sun's constantly changing position relative to a building and the unpredictable distribution of cloud cover relative to the sun's position make design for solar and daylighting a challenge. Simulations can use an annual weather file that contains one example of how they may interact, a peak file that contains the most extreme conditions, or a general probability of how they may interact at a given time.

The sun's energy on a surface—one square foot of window, for example—is called insolation. A south-facing window at 10 a.m. may receive insolation of 250 Btu/h per ft^2 of window area. Over the course of 10 hours, the window may receive 2000 Btu per ft^2. This quantity can be translated into a heat source or a cooling load, once this energy has been transferred into a building. Available solar energy depends on cloud cover and the angle at which it reaches the Earth, and is easily mapped by design simulation software.

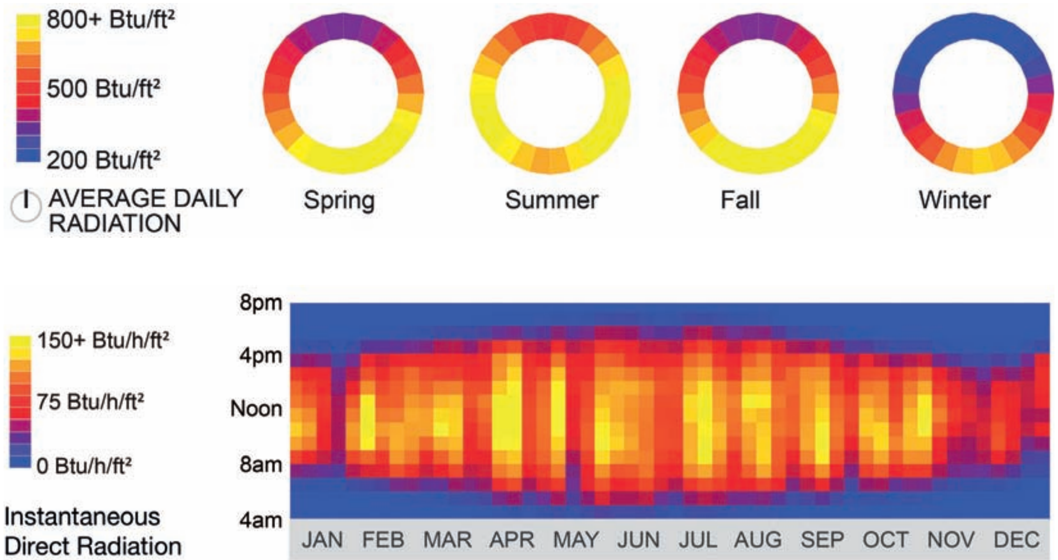
A weather file contains logs of direct irradiation, measured perpendicular to the sun's rays; global horizontal irradiation, which is measured on a flat horizontal surface; and global diffuse radiation, which includes all reflected radiation that does not come directly from the sun. Diffuse radiation is measured by locating a small disc between the instrument and the sun, thus removing the direct radiation component.

Cloud cover blankets the Earth, keeping heat from escaping. Cloudless nights tend to create colder mornings, due to radiative cooling. Clouds not only trap airborne heat beneath them, but also reflect radiant heat downward that would otherwise be lost into space.

Cloud cover is measured as an average percentage of sky coverage. The distribution of clouds constantly changes, and whether the sun reaches a building is entirely dependent on a specific vantage point at a specific time. Software often calculates the probability of the sun being blocked by clouds at a given moment.

Some ways that solar irradiation and cloud cover are used in building design and simulation are:

- Windows allow direct heat gain, which must be controlled as a heat source. Peak solar loads often drive mechanical system selection, sizing and cost.
- Irradiation falling on opaque surfaces increases conduction heat gains through the building's envelope, called sol-air gains.



4.10 and 4.11

Solar roses from Central Park in New York City show the average daily amount of solar energy on each vertical segment of a cylinder. Since solar angles are symmetrical about the solstices, each season was centered on an equinox or solstice. The lower images show radiation on a horizontal surface for each hour and day of the year from the same weather file.

Source: Autodesk's Ecotect output. Courtesy of Callison.

- Terrain that faces the sun's path may receive many times more solar irradiation than slopes facing gently away from it.
- Peak cooling loads are often defined as days with no clouds and peak solar irradiation, though many other factors can affect peak loads.
- Peak heating loads are often defined as days with full cloud cover and no direct solar gain.
- Cloud cover is the defining variable in daylighting design. A completely overcast sky is ideal for daylighting, since light is more evenly spread over the sky dome with less chance of direct or reflected glare from the sun, as discussed in Chapter 8.

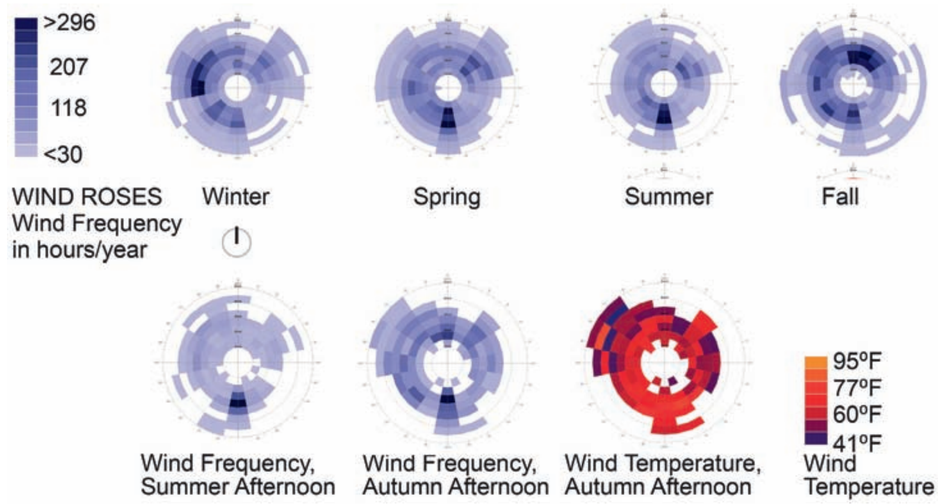
Micro-climate factors include:

- Clouds and fog often form near water bodies; several miles inland, conditions are generally less cloudy and foggy.
- Low clouds are driven by micro-climate wind effects of terrain near the Earth's surface, though above several hundred yards they are mostly driven by non-terrestrial forces.
- When the sun's ultraviolet rays hit pollution from vehicle combustion exhaust and industrial processes, smog is created. Smog tends to be worse in the summer, especially when it is contained by mountains such as in Los Angeles or Mexico City.

WIND

Wind may be channeled through urban canyons into uncomfortable high-velocity wind and swirls, while the right design can channel a breeze's cooling effects through a building to reduce or eliminate a mechanical cooling system. Wind is caused when areas with lower air densities (barometric pressure) pull air from adjacent areas with higher densities. Wind is described in terms of speed and direction and most often displayed as a wind rose, showing the frequency with which each combination of speed and direction occurs.

Wind speed increases at increasing elevations above the surrounding terrain according to a function called the wind gradient. Wind speeds at airports are typically measured at 33′ above the ground, so wind speeds from weather files will over-predict wind speeds for ground-level buildings and under-predict for taller buildings. Generally, a few hundred yards above the surface of the Earth (above the boundary layer), wind flows at much higher speeds, without interacting significantly with the terrain below. These wind patterns circulate warm and cold air across the globe.



4.12

Wind roses graphically display wind data from a Manhattan TMY3 file with increasing frequency shown in a darker color; increasing wind speed is shown as a distance from the center. From these charts, summer winds can be read as typically coming from the south, while winter winds are generally from the west. Wind roses can be looked at in much greater detail as well: during summer afternoons when natural ventilation is most appropriate, breezes are consistently from due south. An outdoor restaurant designed for autumn use has another reason to face south, since the breezes from the south are comfortable temperature-wise as well, whereas colder winds are coming from northeast and northwest.

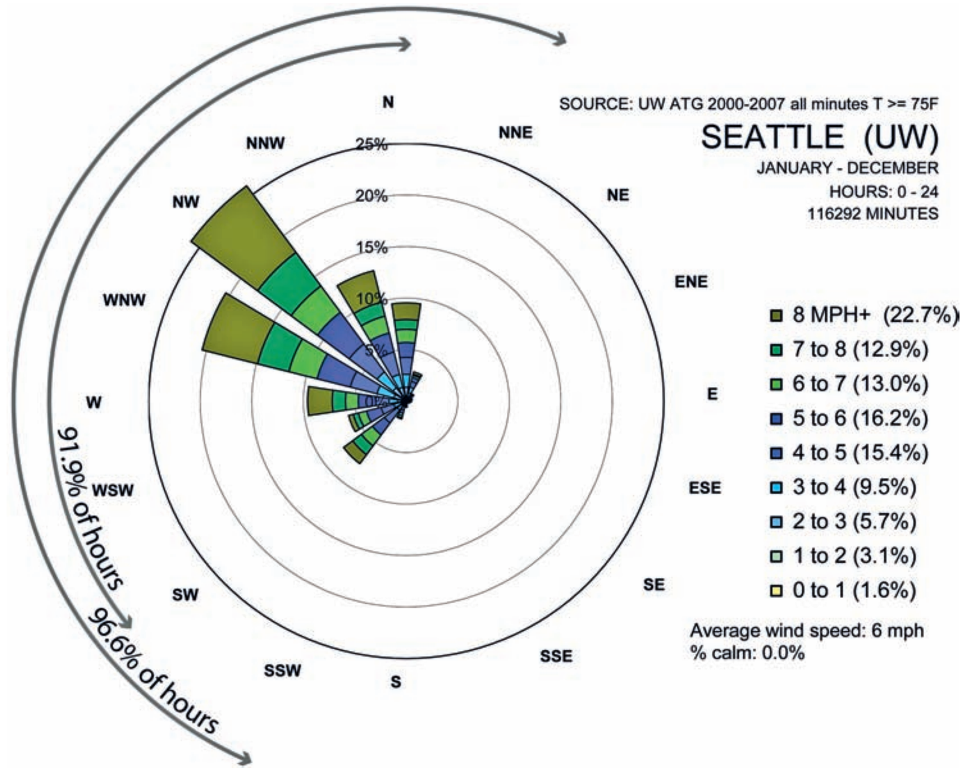
Source: Output from Autodesk's Weather Tool. Courtesy of Callison.

Buildings, trees, hills and mountains shape the wind near the ground, increasing wind speed or causing eddies as it flows around them and creating myriad localized wind conditions. For example, cold winter winds may come from the north generally in Seattle, but these same winds may come from the northeast or northwest on a given site due to local terrain or nearby buildings.

Wind studies on buildings may use physical models in wind chambers, computer-based Computational Fluid Dynamics (CFD) software for point-in-time analysis, or bulk airflow analysis by hand or as part of hourly energy modeling; these methods are covered in Chapter 9.

Some ways that wind is used in building design and simulation are:

- Wind can be used as part of a natural ventilation strategy that provides fresh air and/or cooling. This requires a wind-responsive building orientation, shape, interior volume, and operability at each floor.
- High winds can cause air leakage (infiltration), increasing energy loads; for this reason, blower door tests (used to verify infiltration levels) cannot be performed when outdoor wind levels are above a certain threshold.
- Wind scoops at the rooftop can be designed to draw fresh air in and exhaust stale air, and can be part of an evaporative cooling system.
- TMY file months are not selected based on typical wind direction, and contain a low weighting for wind speed, so wind energy simulations should be based on other sources.
- Wind power integrated into buildings is more of a gesture than an effective power generation strategy.
- Naturally ventilated spaces require a well-thought-out façade design to control wind gusts that would ruffle papers and create discomfort.
- Outdoor spaces in urban or windy areas can use simulations to anticipate and avoid eddies, downdrafts, or updrafts at entries and plazas.



4.13

Local wind data has been compiled to show frequency, direction, and speed during those hours of the year where the outdoor air temperature is above 75°F. This data helped determine that wind direction and speed were consistent enough to provide natural ventilation cooling for the offices at the University of Washington Molecular Engineering & Sciences Facility.

Source: Courtesy of ZGF Architects.

- Wind chill is an experiential metric that estimates how much additional heat a person loses when exposed to wind in addition to cold air temperatures. At 10°F, a 33 ft/s wind speed will cool off a human roughly equivalent to –13°F with no wind.

Micro-climate factors include:

- Buildings create nearby positive and negative pressures that can be used to draw air through a building. Computer-based wind simulations are used to test for the location and strength of these pressures.
- Wind data is taken from wide-open airports, so wind speeds and directions are likely to be different for low-rise buildings in urban contexts. These sites require simulation, research, or experience to anticipate effects.

PRECIPITATION AND STORMS

Our lives depend daily on fresh water, which is most often supplied by rain and melting snowpack. Precipitation determines the density of vegetation in each region, causes flooding in many parts of the world, and accompanies thunderstorms, hurricanes, and other storms. Some of the most important strategies for human well-being and sustainability depend on rainfall and water, but these are beyond the scope of this book.

Precipitation occurs when clouds or airborne humidity are cooled until they condense sufficiently for gravity to counteract buoyancy. Clouds and airborne humidity can be cooled by expansion while rising, when encountering a mass of cooler air or through other means. Precipitation is measured in inches of rain or snow; an inch of rain can be equivalent to between 3 to 20 inches of snow, depending on snow density.

Many areas experience localized weather events, including lightning strikes, seasonal dust storms, typhoons, hurricanes, high-speed wind gusts, and monsoons. The effects of these are not captured entirely by a weather file but may affect building design. For example, dust storms may reduce the amount of time each year that natural ventilation can be used. Searching for additional information is always important in analyzing an unfamiliar climate.

Some ways that precipitation is used in building design and simulation are:

- Since precipitation is generally colder than the air temperature near the ground and since water stores heat well, rainfall absorbs energy from a roof's surface before it drains away.
- Rain can ruin the effectiveness of green roofs' insulation value in cool, rainy seasons. Rain penetrates through the thin soil layer to cool the roof, and the soil moisture-holding capabilities later lose additional heat to evaporation.
- Deep, dry snow creates a thermal blanket, increasing the effective insulation value of a roof assembly.
- Snow creates a host of building science issues in cold climates that need to be carefully considered.

Micro-climate factors include:

- Precipitation increases on windward slopes and decreases on leeward slopes.
- Precipitation increases near water bodies due to higher local humidity levels.

CONCLUSION

The art of climate-responsive design was discarded by many architects in the twentieth century, due in part to being able to create indoor comfort with brute force using abundant fossil fuel energy. With the costs of fossil fuel energy use now known to be environmentally catastrophic, creating comfort within buildings requires a more sophisticated response to outdoor conditions.

Running and understanding simulations require comprehension of each of these climate factors, as well as how a given site may have a micro-climate different in some ways from the nearest weather file. From an analysis of the climate as part of a project kick-off, to the investigation of strategies through all design phases, low-energy buildings depend upon responding to each aspect of climate appropriately.

ADDITIONAL RESOURCES

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http://cliffmass.blogspot.com/
Olgyay, V. (1963) *Design with Climate: Bioclimatic Approach to Architectural Regionalism*, Princeton, NJ: Princeton University Press.
Users Manual for TMY3 Data Sets http://www.nrel.gov/docs/fy08osti/43156.pdf
Wilcox, S. and Marion, W. (2008) *Users Manual for TMY3 Data Sets, NREL/TP-581–43156,* April. Golden, CO: National Renewable Energy Laboratory.

4.1 CLIMATE ANALYSIS

Project type:
Eleven 24-story residential towers and one 14-story office tower

Location:
Mumbai, Marahastra, India

Design/modeling firm:
Callison

This climate analysis for a warm, tropical area considers solar irradiation, temperature, and wind direction and speed to determine site planning issues. Other climate analysis statistics were not as important for this site planning exercise.

Overview

At project kick-off, the design team analyzed the climate to determine optimum building orientations. The rule of thumb for tropical climates includes protecting east, west and roof façades from solar gain, with glazed areas concentrated on the south and north.

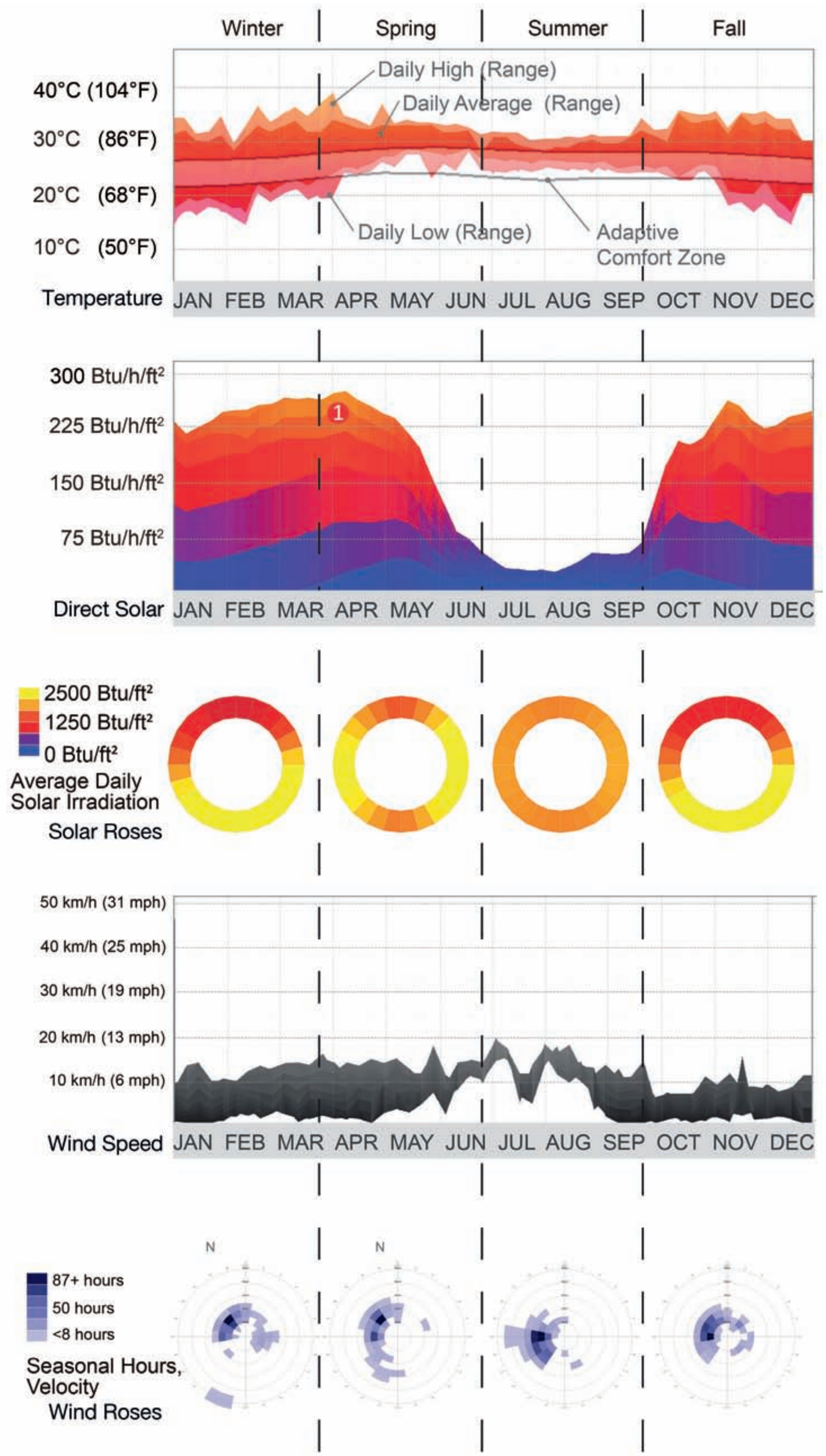
Residential towers in India are required to have light and operable windows in every room. Designs for mid-range condos typically include 3–6 units per elevator and stair core, with a single tower design often repeated and rotated around the site, making design for wind-driven cross-ventilation difficult.

Interpretation

Temperatures are above the indoor comfort range throughout the year—the adaptive comfort range is shown in light colors across the temperature profile. The hottest period is the Fall and Winter, and the coolest is the humid Summer monsoon. Solar gain throughout the year is very intense, except during the Summer monsoon. The solar roses show a southern bias during the hottest periods (Fall and Winter), an East–West bias in Spring, and nearly uniform irradiation during the monsoon, due to solar energy being diffused by clouds.

Afternoon winds that could aid in cooling tend to come from the west and northwest throughout the year. Orienting operable windows to these directions would allow through breezes to reduce dependence on mechanical cooling. The weather station is located only 3 miles southwest of the site, with no hills or terrain between them, so the team felt the climate data was reliable enough.

For these reasons, the team offered an initial design with the residential building having broad east and west façades. The eastern façade contained courtyards, so each unit would have light, ventilation, and through breezes. The western façade contained the majority of living spaces with balconies, providing deep shade structures for solar protection, large doors for through breezes, and a shading response to protect areas not already shaded.



4.14

Mumbai data.

5

Planning and Goal-Setting

A goal is a dream with a deadline.
—Napolean Hill

The goals we set affect the way we design buildings. Goals for first costs and lifecycle costs, energy use, water use, daylight, and many other aspects of a project that are set firmly during the site planning process become a project's DNA, guiding decisions from the kick-off meeting through construction and occupancy.

This chapter and the case studies provide an insight into the types of energy-related goals that may be set. For example, a goal of Net Zero Energy puts every financial decision against the cost of renewable energy, freeing up the design team from studying poor-performing options. Space-by-space goals, such as achieving 2% minimum daylight factor in 80% of every classroom, affect massing, orientation, glazing selection, and interior color choice, among others. The large number of project inputs can crowd out sustainability unless explicit goals are set.

During site planning, geometric expressions of a program are explored for their effect on achieving explicit and implicit project goals. The design moves from this phase exert a huge influence on the success or failure of meeting the team's energy goals. The second part of this chapter and the case studies look at testing geometric expressions with design simulation.

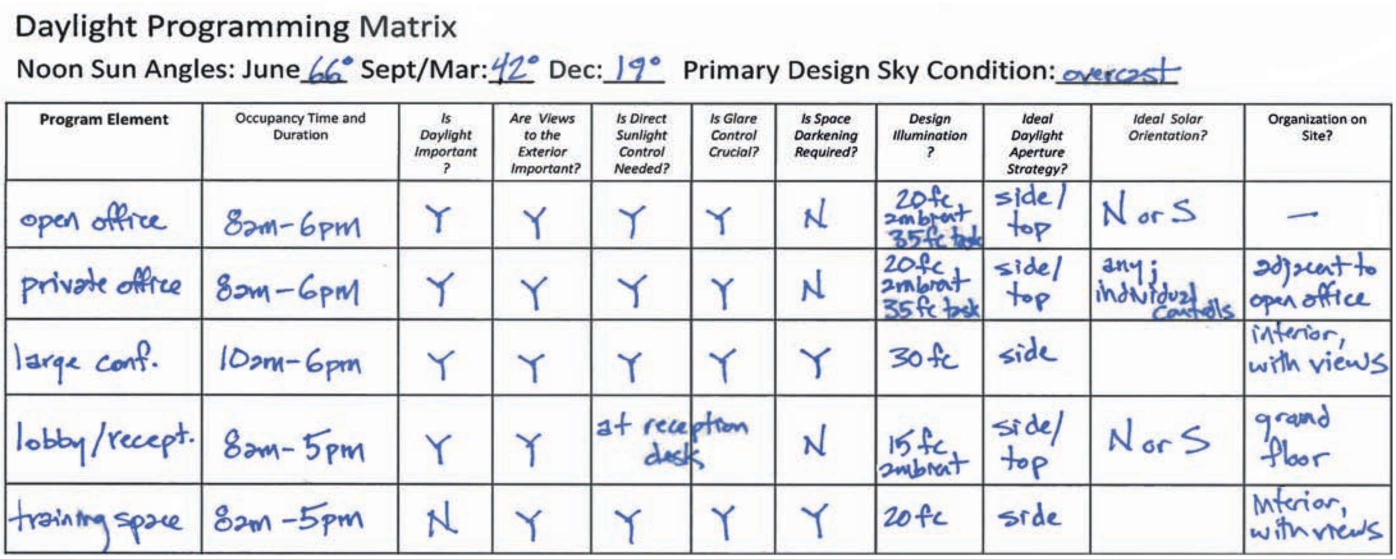
For example, the Living Building Challenge certified Bullitt Center in Seattle, designed by Miller Hull, could not have achieved Net Zero Energy goals without increasing the floor-to-floor height. This effort was informed by early daylighting simulation, see Case Study 10.7. As another example, the orientation of the Federal Center South in King County, Washington, was informed by a shoebox energy modeling run by ZGF Architects during the competition phase, see Case Study 5.4.

Making the most of the money available is a challenge on nearly every project. Setting goals early reduces the cost of achieving the same goals if they are set later in the process. This is in part because geometric design moves are more difficult to change later in the process, so only expensive equipment upgrades are available to meet the new goals. For projects where a sizeable decrease in operating cost can be realized, the reduced cost of energy bills or financing due to a higher appraisal can sometimes be used to increase the available capital cost.

GOAL-SETTING

Two types of goals will be discussed: project-wide goals and space-by-space goals. Setting project-wide energy goals is a complex balance between the security of repeating past efforts, the desire to improve performance, and the perception of costs. The 2030 Challenge offers a great balance for many projects, since this goal is specific, generally achievable with off-the-shelf technology, and is easy to understand and communicate.

Space-by-space goals can be equally important, and can be achieved, in many cases, regardless of overall project goals. Determining criteria for each space for daylight, views, and comfort at the programming phase is a powerful way for a design team to understand the program before they mass



Daylight Programming Matrix

Noon Sun Angles: June 66° Sept/Mar: 42° Dec: 19° Primary Design Sky Condition: overcast

Program Element	Occupancy Time and Duration	Is Daylight Important ?	Are Views to the Exterior Important?	Is Direct Sunlight Control Needed?	Is Glare Control Crucial?	Is Space Darkening Required?	Design Illumination ?	Ideal Daylight Aperture Strategy?	Ideal Solar Orientation?	Organization on Site?
open office	8am-6pm	Y	Y	Y	Y	N	20fc ambient 35fc task	side/top	N or S	–
private office	8am–6pm	Y	Y	Y	Y	N	20fc ambient 35fc task	side/top	any; individual controls	adjacent to open office
large conf.	10am-6pm	Y	Y	Y	Y	Y	30fc	side		interior, with views
lobby/recept.	8am-5pm	Y	Y	at reception desk		N	15fc ambient	side/top	N or S	grand floor
training space	8am-5pm	N	Y	Y	Y	Y	20fc	side		interior, with views

5.1

A daylight goal-setting exercise can help the project team establish criteria for each programmed space. These criteria can help orient each space within the overall massing, and define space-by-space targets for later design simulation.

Source: Courtesy of Chris Meek, University of Washington Integrated Design Lab.

the building. Space-by-space goals are used as the criteria for success in later design simulation efforts.

Goals are much easier to set and achieve when the full project team is assembled at the outset. When project teams are fragmented, and mechanical engineers and energy analysts are not brought on board until midway through the design process, substantial energy and cost savings are already beyond reach.

Project teams that have set Big, Hairy, Audacious Goals, known as BHAG and popularized in *Built to Last: Successful Habits of Visionary Companies* (Collins and Porras, 1997), can be rewarded by energy-efficient buildings that have similar costs as typical buildings. A BHAG is on the edge of achievable; it motivates a team to consider a project with a fresh set of eyes. The Net Zero projects in this book achieved their energy goals mostly with off-the-shelf systems; however, the goals of being Net Zero spurred the teams to approach the design differently, which encouraged creativity that led to energy reductions.

- For example, the kick-off eco-charette for the LEED for Neighborhood Development Platinum (Stage 2) Ever Vail project began with an introduction by Vail Resorts CEO. He made it clear that Vail Resorts did not sell skiing, they sell access to nature, and so nature's health was integral to their philosophy. The project team referred back to this talk many times, since they knew every decision would be weighed against this philosophy.
- The goal of achieving the Living Building Challenge, which includes Net Zero Energy (NZE) certification, required the Bullitt Center project team to study daylighting, energy production, skin-to-core depths, and other facets of the building design at the outset to ensure performance. With the difficult goal of NZE on a 6-story project, every aspect of the building had to work together.
- For DPR Construction's Energy San Diego office, designed by Callison, KEMA Energy Analysts were appointed to be the energy champion. Since the explicit goal at the outset of the project was to achieve NZE, many options for standard buildings did not need to be studied. This freed up the creative energy of the team to explore only highly efficient options within a payback timeframe of the lease.

Conversely, when energy goals are not set quantitatively by leaders, sustainability efforts get bogged down later in design by middle managers requesting incremental cost analysis. Since each building contains a complex interaction of geometries, materials, and systems, costing exercises take a good deal of time to correctly assess first cost and operating cost implications. Unfortunately, many good strategies fall victim to myopic costing exercises that focus a single aspect of a building.

5.2

For the kick-off eco-charette for the Ever Vail project, nearly 40 people representing all disciplines gathered to thrash out ideas to achieve sustainable project goals. The masterplan for Ever Vail achieved LEED for Neighborhood Development (Pilot) Platinum Stage 2 certification.

Note: Photos, renderings, and data are courtesy of Vail Resorts Development Company and may not be reproduced without permission.

Results for Estimated Energy Use

Energy	Design	Target	Median Building
Energy Performance Rating (1-100)	N/A	99	50
Energy Reduction (%)	N/A	60	0
Source Energy Use Intensity (kBtu/Sq. Ft./yr)	N/A	89	222
Site Energy Use Intensity (kBtu/Sq. Ft./yr)	N/A	41	103
Total Annual Source Energy (kBtu)	N/A	10,659,154	26,647,885
Total Annual Site Energy (kBtu)	N/A	4,947,347	12,368,369
Total Annual Energy Cost ($)	N/A	$ 68,324	$ 170,811
Pollution Emissions			
CO2-eq Emissions (metric tons/year)	N/A	745	1,861
CO2-eq Emissions Reduction (%)	N/A	60%	0%

Facility Information Edit

81658
United States

Facility Characteristics Edit

Space Type	Gross Floor Area (Sq. Ft.)
Hotel	120,000
Total Gross Floor Area	120,000

* The Median Building is equivalent to an EPA Energy Performance Rating of 50.

Estimated Design Energy Edit

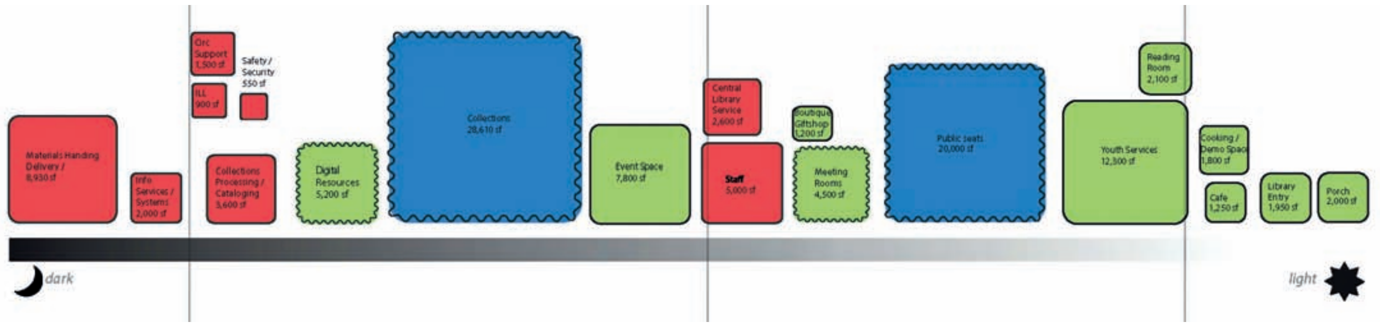
Energy Source	Units	Estimated Total Annual Energy Use	Energy Rate ($/Unit)
Electricity - Grid Purchase	kBtu	N/A	$ 0.020/kBtu
Natural Gas	kBtu	N/A	$ 0.008/kBtu

Source: Data adapted from DOE-EIA. See EPA Technical Description.

5.3

Target-Finder output for a hotel in Vail, Colorado. Target-Finder displays several types of metrics: Site, Source, Cost, and Carbon Emissions. This information is based on the Commercial Building Energy Consumption Survey (CBECS) data.

Source: https://www.energystar.gov/index.cfm?fuseaction=target_finder.



5.4

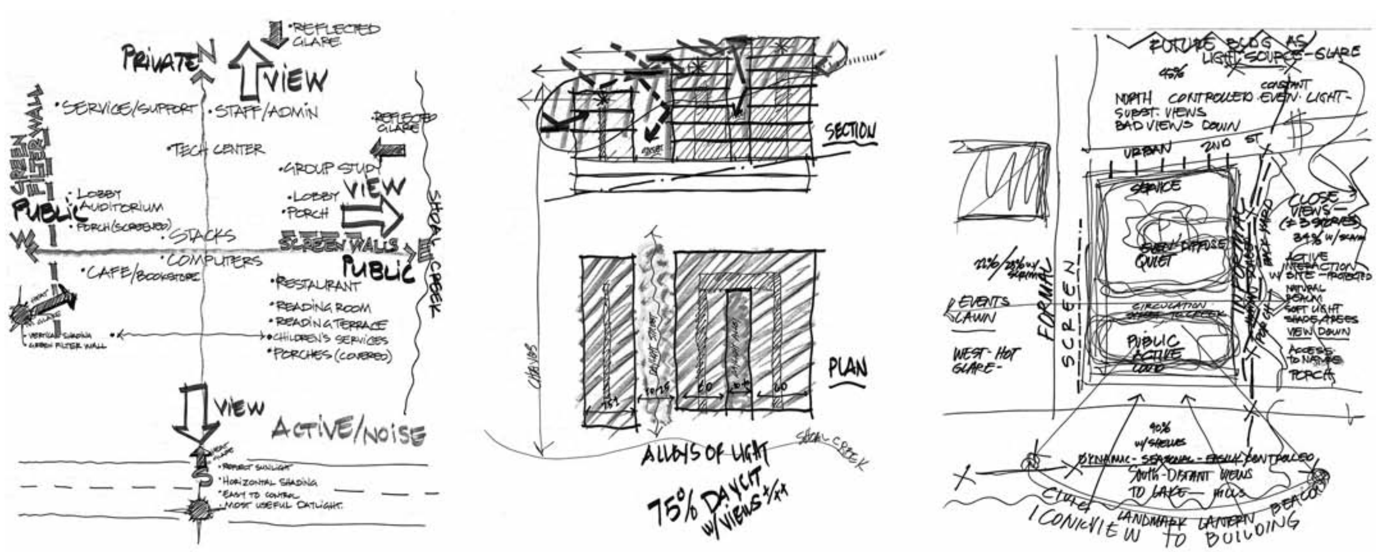
Near the beginning of the design process for the Austin Central Library, the programmed spaces were diagrammed, showing the relative importance of light for each programmed space. Additional diagrams were also done for connection to the outdoors and the desire for privacy. These informed the early massing options.

Source: Courtesy of Lake Flato Architects and Austin Central Library.

As an example, increasing the quality of glazing on a project may reduce peak heating and cooling loads, which may in turn allow a reduction in the boiler and chiller sizes and associated ductwork. Reducing the ductwork size may reduce the necessary floor-to-floor heights, allowing an extra floor or an increase in the ceiling height, which may then allow more daylight and decrease the lighting load. Often only the increased cost of the glazing is considered, especially in the so-called value engineering phase.

To take the example further: when a mechanical designer faces glazing alternatives late in the design process, the worst-performing option will be (rightly) chosen to size the system. Since the engineer has only time and the fee to design one system in great detail, the system size and layout get locked in based on the worst case. If the client decides later to go with improved glazing, reducing energy use by 4%, they will have missed both first cost and energy savings.

Had the decision been made earlier, with time to design a mechanical system appropriate to the improved envelope, an energy savings of 8% might have been realized, due to a smaller and more effective system. In many cases the client pays more for late decision making, and then is convinced that sustainable design costs more. The Rice Fergus Miller office (Case Studies 10.3 and 10.5) client paid only $10/ft^2$ for the highly advanced mechanical system—significantly less than for a standard mechanical system for a standard building. This was due to a great design team and fixed energy goals set during the kick-off eco-charette.



5.5

Early diagrams by Lake Flato Architects explore the site and massing options.

Source: Courtesy of Lake Flato Architects and Austin Central Library.

MENU-BASED GOALS

Menu-based systems that let design teams choose which sustainability strategies to pursue are becoming more popular. They are now being integrated into building and energy code such as the International Green Construction Code and the International Energy Conservation Code. Leading the way for voluntary systems is the United States Green Building Council's (USGBC) Leadership in Energy and Environmental Design (LEED) rating system, with over 40,000 buildings certified worldwide.

The USGBC has radically improved the understanding and application of sustainability with their voluntary rating systems. They have increased the general knowledge and terminology of architects and the public, transformed the materials industry, and expanded the use of energy modeling; the robust health of the green building movement in the USA has been largely based on the success of their rating systems. While this book contains critiques of LEED, the transformation that has taken place due to their efforts is awe-inspiring.

There are several reasons why the LEED system has been criticized for inconsistent energy use reductions across their range of certified buildings:

- While projects certified under LEED 2009 have been required to reduce energy use, projects certified under earlier systems often opted for minimal energy use reductions.
- Energy modeling using ASHRAE 90.1 (the LEED referenced method for larger projects) is not intended to predict energy use. While ASHRAE 90.1 results in a percentage of energy savings, this is not in comparison to an average or prototypical building—the comparison building is unique to each project.
- Actual building energy performance is due to many things beyond the control of the design team (Newsham *et al*., 2009).

One downside to menu-based goals is that, unless a formal energy goal is set in addition to the menu-based goal, the team is often left costing each option. This can lead to the situation described above where the mechanical design is sized to meet the lowest-performing option, reducing the performance and wasting money.

ENERGY GOALS

Goals provide a measure against which future decisions will be evaluated to determine success. Formal goals are a way to communicate across the entire project team so individual decisions are made towards a common purpose. It's easy to underestimate the downstream impact that formal goals, especially quantitative goals, can have on future decisions within design, construction and operation.

Energy goals need to be understood by project teams for what they include and exclude. Some of the most common types of energy goals are described below.

Percentage Energy Savings Using Energy Cost Budget

The Energy Cost Budget method compares the cost of energy for the 'designed' building against the cost of energy for a fictitious baseline building with a similar geometry but code-compliant components

City	Miami	Houston	Phoenix	Atlanta	Los Angeles	Las Vegas	San Francisco	Baltimore	Albuquerque	Seattle	Chicago	Denver	Minneapolis	Helena	Duluth	Fairbanks
Medium Office	39	42	40	41	33	37	38	45	38	42	48	41	54	48	57	77
Stand-alone Retail	62	63	60	61	44	56	50	72	61	65	81	69	93	83	104	145
Quick Service Restaurant	535	549	538	561	496	541	524	609	567	575	657	604	713	663	765	949
Large Hotel	99	108	100	116	105	105	113	127	119	124	138	131	150	144	163	196
Mid-Rise Apartment	39	39	38	38	31	36	33	42	37	38	47	41	54	48	59	76

http://cms.ashrae.biz/EUI/

5.6

US Department of Energy (DOE) Commercial Building benchmark Energy Use Intensities (EUI) from October 2009, in kBtu/sf/year. These EUIs represent buildings that are intended to be compliant with ASHRAE 90.1–2004. The full list includes 16 commercial building types.

Source: http://cms.ashrae.biz/EUI/.

and assumptions. This method is used primarily to achieve LEED points using ASHRAE 90.1 or meet energy code targets, and is not intended to predict Energy Use Intensity (EUI). A daily schedule of normal and peak energy charges from the utility are assessed based on the time of day at which energy is used, resulting in a comparative energy cost. The baseline building generates the cost budget, and the proposed design is measured against it, resulting in a percentage savings.

Annual Energy Use Intensity

Goals such as the 2030 Challenge, 2030 District targets, and Passivhaus measure against EUI: energy use per square foot per year (kBtu/sf/year).

The 2030 Challenge has become the standard for many architecture firms and government agencies as it is straightforward, based on surveys of existing buildings in many climates, and generally achievable with existing technology. Its goals are based on savings as compared to the US Commercial Building Energy Consumption Survey (CBECS) from 2003. The US Department of Energy (DOE) Target-Finder, a two-minute online tool, can provide a 2030 Challenge target and other EUI goals based on project size, typology, and location. However, some hypologies are not covered in the survey, and many sustainable design experts have concerns about the accuracy of the data. ASHRAE offers a standard benchmark EUI based on current energy codes for each climate zone shown in Figure 5.6.

The difference between the site and the source EUI goals seems subtle, but can have a major influence on design. Site EUI simply sums energy used within the building from electricity, natural gas, and other sources, subtracting any energy generated on site.

A source EUI, such as that estimated by Target-Finder, multiplies site electricity energy use by 3.34 (*Performance Ratings*), while natural gas is multiplied by 1.047. The source penalty for grid-based electricity is largely due to the prevalence of coal, which is converted to electricity at below 50% efficiency. In addition, centralized electricity requires hundreds of miles of transmission lines and equipment, with transmission losses averaging 7.4% (D&R International, 2011) depending on distance and grid quality.

Since grid-based electricity is penalized, source EUI goals favor on-site combustion, renewable energy, and reducing cooling (which uses electricity primarily) at the expense of heating using natural gas. Most EUI goals are based on source energy use since it corresponds more closely to carbon emissions.

Net Zero Energy (NZE) Goals

Net Zero Energy (NZE) goals are usually calculated to match operational EUI with available renewable energy on an annual basis. The Bullitt Center and the Berkeley Library first calculated the amount of photovoltaic (PV) and solar thermal energy they could fit on the roof, and then set an operational EUI target based on that number. In order to be NZE-ready, the Rice Fergus Miller office design team similarly calculated the rooftop PV potential and then designed the building to achieve a corresponding EUI. They can add photovoltaics to the roof over many years to achieve NZE.

First-world NZE buildings are usually tied into the grid, so they can both draw electricity from the grid when renewable energy is not available and push it back to the grid when it is. During an average year, the meter will balance to zero. NZE is very difficult, and not achievable on every project or site. It is often calculated using site electricity balancing to zero (instead of source energy), so the net impact of the energy on carbon emissions into the atmosphere is not zero.

A project that achieves Living Building Challenge (LBC) certification is, by definition, sustainable. Averaged over the course of a year, it uses no water or energy, produces no waste, and achieves other rigorous performance goals. While the LBC is menu-based, it takes the opposite approach to LEED: all items are required to be achieved. This removes the uncertainty and provides clear goals. A client or project team that is considering the LBC needs to set this goal at the project outset due to the technical complexity of achieving it.

Passivhaus

The Passivhaus standard originated in Europe, where it has guided tens of thousands of buildings of all types. The free, voluntary standard has a baseline EUI (often 4.75 kBtu/ft^2/year) for space heating and cooling. There are other EUI criteria for overall performance, mentioned in Case Study 10.4. Passivhaus buildings come close to achieving the 2020 threshold of the 2030 Challenge even before considering any renewable energy.

Peak Heating or Cooling

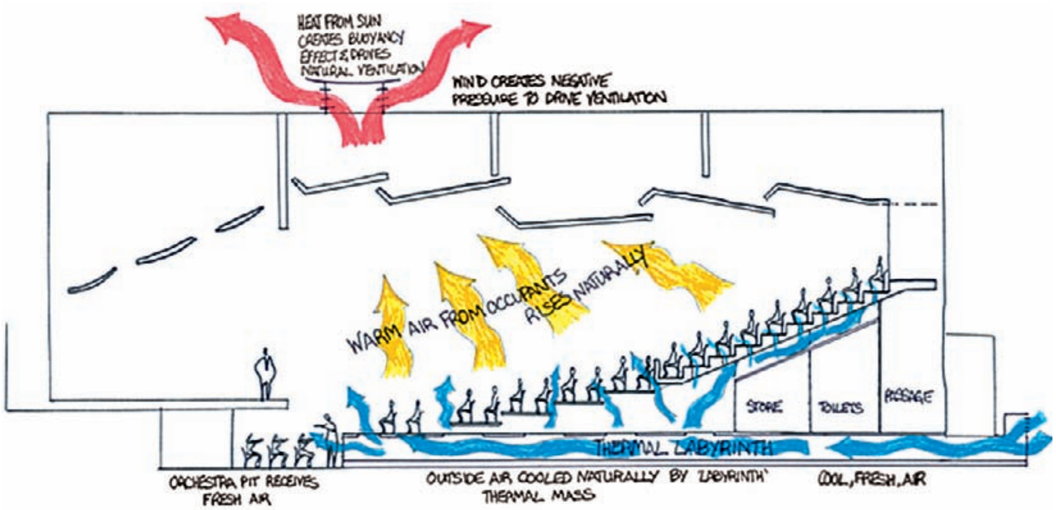
Mechanical systems are sized to meet peak loads, so reducing peak loads reduces the project costs, as well as generally reducing annual energy use. Peak loads are driven by solar gain and conduction from peak outdoor temperatures, in addition to loads from normal building use.

Peak energy use is associated with additional energy costs, up to 20 times normal energy costs. This is because power plants are sized and built based on peak demand. Utilities ramp up production to meet the late afternoon (cooling) and early morning (heating) peak demands since they occur simultaneously across regions. For this reason, shifting peak loads later in the day using thermal mass, or using heat storage systems, can reduce both mechanical costs and energy charges.

The project team for the Molecular Engineering Building at the University of Washington, led by ZGF Architects, reduced peak loads by 50% in order to eliminate the need for mechanical cooling in the office spaces. See Case Study 9.1. The façade was designed to control solar gain (see Chapter 7), reducing the need for artificial light through daylighting (see Chapter 8), and optimizing glazing percentage to reduce conductive load through the glass.

Carbon Footprint Goals

A comprehensive climate change strategy at the national or international level would put a cost on carbon, so targeting carbon directly aligns with this possibility. A carbon footprint can be very broad, including transportation to and from a building and the energy embodied in construction materials. It can also be



5.7

Concrete "earth tubes" beneath the seating use thermal mass and evaporative cooling to maintain comfort even during peak conditions. This system was proposed early in the design phase, chosen as a project goal, and successfully eliminated the cost and energy use associated with a mechanical cooling system.

5.8

The Wendouree Performing Art Center in Ballarat, Australia, designed by McIldowie Partners, was able to eliminate the mechanical cooling system due to the use of natural ventilation. This required analysis at the earliest stages of design to prove the concept would work.

Source: Courtesy of WSP Built Ecology, photos © Martin Saunders.

5.9

Earth tubes under the floor.

deep, exploring the long supply chain of aluminum window frames back to the repercussions of materials being extracted from the earth, for example. Because of this, any carbon footprint analysis needs to first define the scope in terms of breadth and depth. An annual energy model can be modified to output carbon equivalents instead of EUI data, but other carbon measurements require research. The Living Building Challenge requires all construction material embodied energy to be offset.

Goals can be set for nearly every aspect of a building's energy use, including:

- Pressurization testing to a certain threshold to ensure minimal air leakage.
- Lighting power density or lighting use factors.
- Use of natural ventilation during appropriate seasons for fresh air or cooling.
- Occupant access to operable windows or other environmental controls.
- Post-occupancy energy use goals, verified after one or two years of occupancy.
- Target glazing percentage—while glass looks great in renderings, it is often the worst performing thermal aspect of many projects.

Space-by-Space Goals

These can be set during the programming phase alongside the more typical goals for adjacency and stacking. They can include daylighting quantities, daylighting qualities (such as daylight from two sides), views, comfort, orientation, proximity to stairs to reduce elevator use, access to natural ventilation, and many others. They are set for each room based on use, allowing a wide variety of goals within a single building. Since design simulation is always performed in relation to an idea of "success," defining success for each space provides a measurement that becomes the criterion for design simulation efforts.

SITE PLANNING AND MASSING

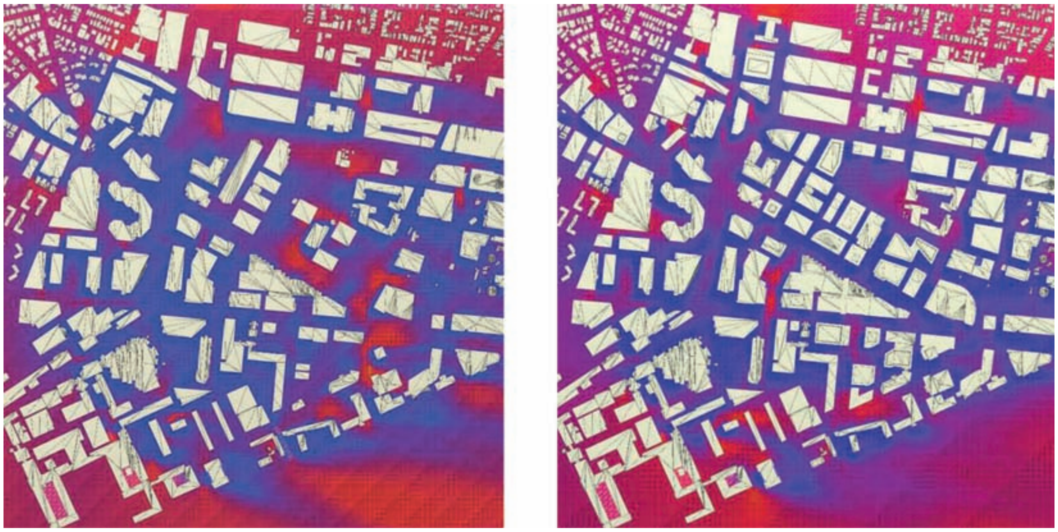
Site planning may involve locating detached homes to maximize views of a lake, massing residential flats on an urban infill site, or locating a hotel and office tower over a retail podium. In most cases, there is freedom for response to the climate analysis—orientating both indoor and outdoor spaces to harvest the right amount of solar energy, daylight, and wind while optimizing glazing percentage.

Some energy reduction strategies need to be considered early or else they are not possible. Each project team will use their specific knowledge of the site, climate, typology, and other project goals to create a list of design priorities once initial goals are set. As with all design processes, good design simulation is exploratory and non-linear.

There are more variables in site planning than can be considered within a single chapter. The examples and case studies provided below illustrate the range of what can be simulated in the planning phase.

Siting

Simulation can be used to overlay multiple aspects (views, proximity to adjacent houses, and site slope) to create a "Desirability Index" as described in Case Study 5.1. Many other types of inputs can be overlaid



5.10

Completed wind speed studies were used to mass new structures to block undesirable winter winds through public plazas. This study was completed as part of the Cambridge Master Plan in Boston, using Autodesk Vasari 3D for a Computational Fluid Dynamics simulation, with false colors representing wind speed. Wind is simulated to come from the upper left.

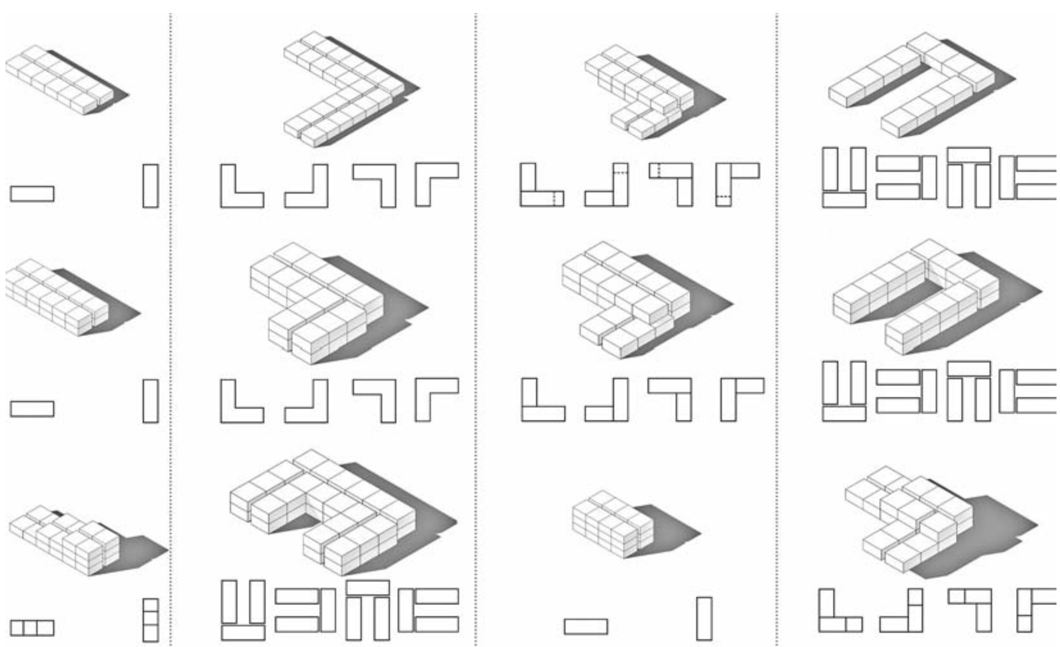
Source: Courtesy of CBT Architects and Planners.

to site buildings to respect existing eco-systems while providing the right access to on-site solar and wind. ZGF Architects used a massively iterative function to comply with sunlight access requirements in Case Study 5.2.

On a site with different building typologies, a thermal loop can share heat between buildings. An office or data center, for example, can share excess heat with nearby residential spaces that generate less internal heat. A thermal loop was incorporated into the design for Ever Vail's masterplan, designed by Callison with Cobalt Engineers.

Massing

An early step in site planning involves massing the program into geometrical blocks driven by typology, such as linear, double-loaded residential towers and hotels, which tend to be bar buildings between 60′ and 75′ wide. Most other typologies have standard widths or depths. A shoebox model of one or more typical widths can be used to study skin-to-core depth, orientation, glazing percentage, or other aspects.



5.11

HMC Architects in-house energy simulations specialists, ArchLab, used eQuest to analyze various single- and double-loaded classroom layouts for overall energy use. This study was done using common room layouts and energy data from existing buildings, and serves as a reference for many other projects as well. The team learned that self-shading has a larger impact on energy use than orientation. Over 50 configurations were compared in each of the four orientations, with the team settling on a design with a U-shaped courtyard.

Case Study 5.4 considers the effects of orientation on peak and annual energy use with a shoebox energy model of a 60′ wide office near Seattle, WA.

In many climates, clustering spaces around a semi-heated atrium can reduce energy use by reducing the envelope area and the associated heat gain and loss, while providing plenty of daylight. An atrium that provides daylight to adjacent spaces often needs solar control, requiring a more detailed type of study to validate increased energy efficiency. Atria can use the stack effect for natural ventilation as well, though rules of thumb are usually sufficient for site planning.

Locating building cores and lobbies can be partially based on climate responses, as Ken Yeang suggests in his books and projects. The building core is generally a net heat producer, as it includes electrical rooms, elevators, and no heat loss when located internal to the building. Locating the core at an edge can be beneficial by blocking late afternoon sun, or exhausting excess core heat directly to the outside of a building. Locating stair towers at the building perimeter can allow them to be daylit, with their verticality also using the stack effect to assist with natural ventilation in some climates.

Solar Studies and Shading

For urban sites, shading from the nearby context can affect solar access and influence a design response. Shading goals may be set in relation to peak design goals, or may be a way to use a more energy-efficient comfort system. Net Zero Energy projects tend to use their entire roof for energy generation, so studying available solar access can help set energy goals.

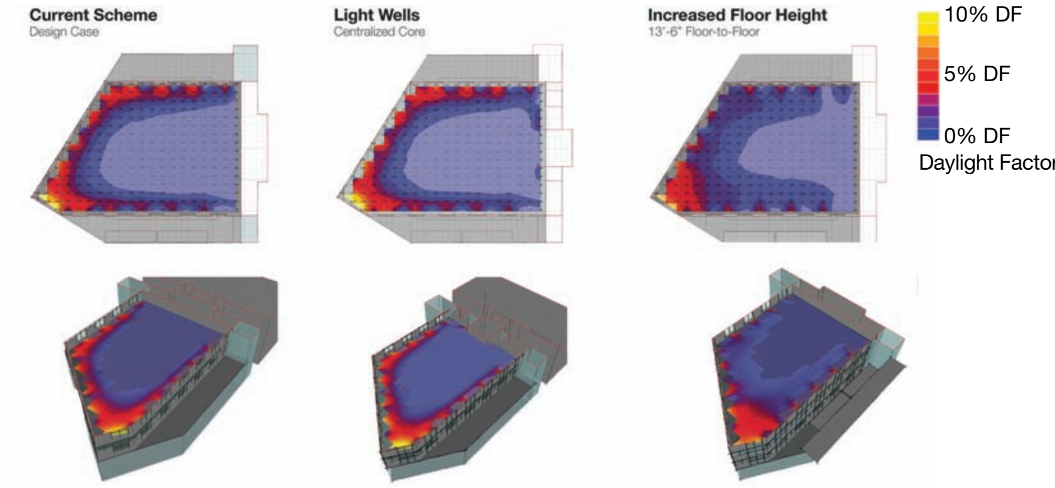
Daylighting

The effect of daylighting goals in most buildings is dependent on floor-to-floor heights and skin-to-core depth. With quick massing models, the daylight factor or daylight autonomy (Chapter 8) can be simulated to balance the floor-to-floor height, glazing percentage, and skin-to-core depth. As a general guide, light penetrates 1.5–2.5 times the head height of the window. For an office building with a skin-to-core distance of 30′, setting a window head height of 12′ in planning should allow good daylighting as the design progresses and can be tested with simulation.

Another worthwhile daylighting goal is to provide daylight from two directions in all living rooms, conference rooms, or other important spaces. This goal helps achieve both good light quality and the chances of achieving the LEED daylighting and views credits.

Natural Ventilation

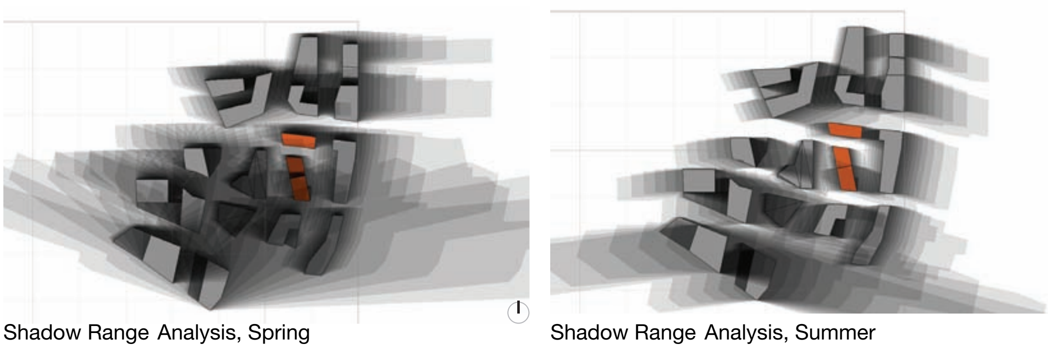
Low-energy projects in climates with mild conditions during portions of the year often use natural ventilation to provide cooling, and introduce fresh air without ductwork fans, or both. Goals for natural ventilation need to be set early, as building interior and exterior massing is critical to success. Hyper-local wind data needs to be collected and interpreted if wind is to drive the natural ventilation strategy in an urban environment. Wind-driven natural ventilation requires early consideration of operable glazed areas, as well as interior layouts and furniture that do not restrict air flow. Stack ventilation systems need to have proper width, vertical height, and temperature differentials to create air movement.



5.12

Miller Hull studied the effects of increasing floor-to-floor height on daylighting for the 6-story, Net Zero Energy targetted Bullitt Center. An early study showed that increasing the floor-to-floor height from 11′4″ to 13′6″ allowed successful daylighting to be achieved on 65% of the floor plate instead of only 23%.

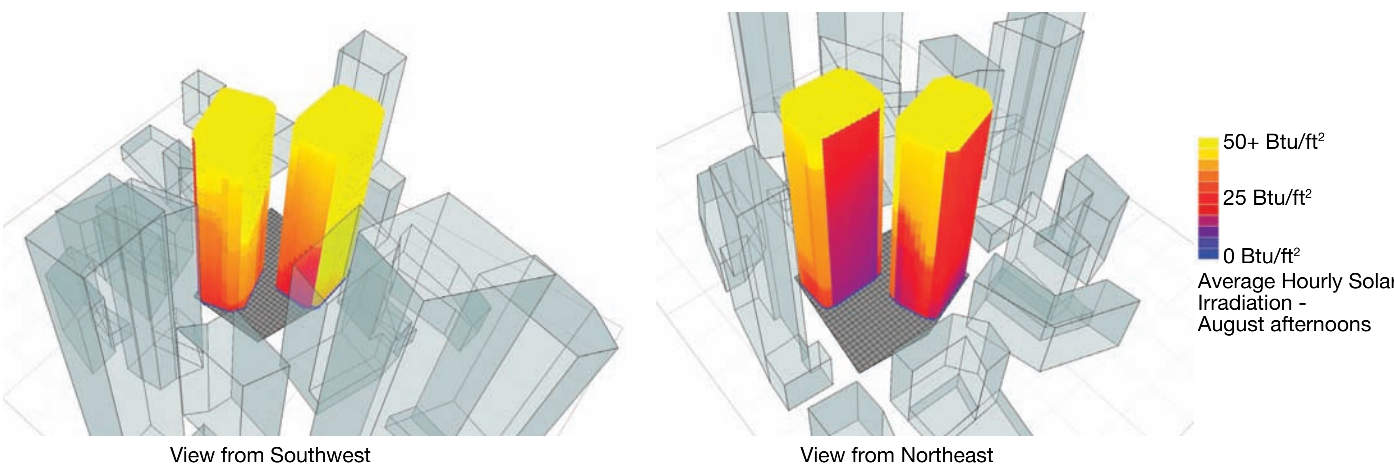
Source: Courtesy of Miller Hull. Ecotect output of Radiance daylighting analysis.



5.13

A shadow range analysis can be used to quickly determine areas that are typically shaded during a portion of the year. For this project, shown in orange, the entire south building is in shadows for much of the spring. During summer, most of the outdoor areas around the buildings are not shielded from sun.

Source: Autodesk Ecotect output.



5.14

A quick massing solar irradiation study can determine the relative solar loads on each façade of a massing model, including any shading attributable to context. This type of study can be done for peak loads or to compare solar radiation during different months. Shading strategies can respond to context and self-shading from this type of analysis.

Source: Autodesk Ecotect output.

CONCLUSION

Every energy-reducing strategy needs to be tested against intuition, experience, rules of thumb and, often, design simulation. Simulation answers questions in relation to the performance criteria defined in overall project goals or space-by-space goals. Goals set early in a project become the DNA of the building, and help the design team make the correct decisions.

Site planning design decisions allow or prohibit the use of sustainability strategies through the rest of the design phases. For this reason, programming, siting and massing designs require consideration of the downstream potential for daylighting, solar gain, natural ventilation, and other strategies.

5.1 SITE LOCATION OPTIMIZATION

Location optimization uses design simulation software in combination with GIS mapping information to composite several variables onto a site. Graphical output allows the client and project team to understand optimal siting easily. This type of simulation can be done with any number of site characteristics, zoning envelopes, wind, and solar aspects.

Project type:
Residence

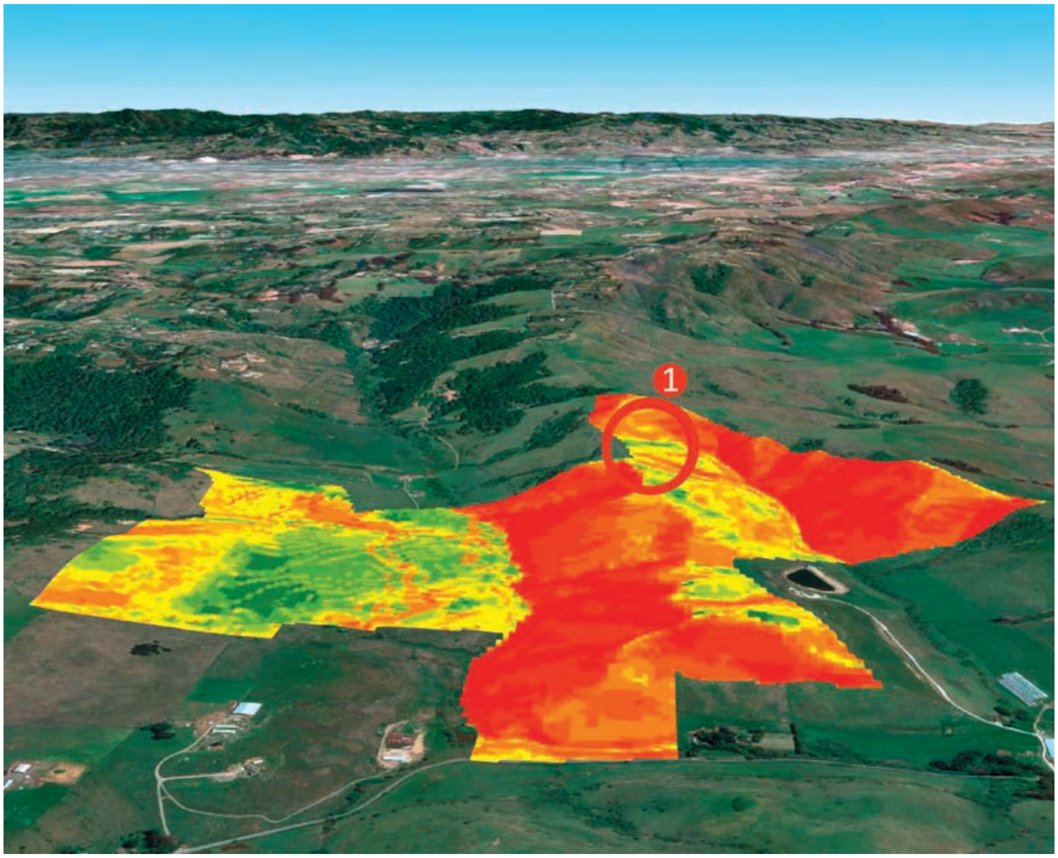
Location:
Sonoma County, CA

Design/modeling firm:
Van der Ryn Architect/Symphysis

Overview

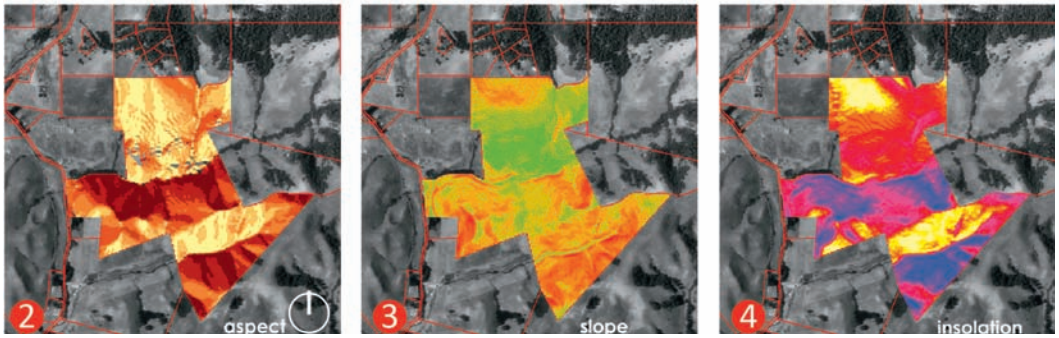
Without proper siting, a structure cannot be designed for passive solar heating. For this house in Sonoma County, CA, a large site offered many opportunities. The clients' main considerations for siting included maximizing winter solar potential, views to the west, and constructing the house in an area with low slope to reduce construction costs and erosion potential.

This case study illustrates the use of Geographic Information Systems (GIS) mapping with multiple criteria to highlight the ideal locations for siting a house, called a "Desirability Index." The client was easily able to interpret the composite image and the house was sited in one of the best areas (1).



5.15

Composite "Desirability Index" mapped over 3D terrain from Google Earth, looking east.



5.16

View Desirability, Slope Desirability, Solar Desirability.

Simulation

GIS is a general term for the ability to layer information onto a map, usually digitally. It allows any 3D data set to be visualized, allowing complex data to be easily interpreted. It has been used to illustrate disease clusters, vegetation densities, pollution dispersal, and urban heat island effect, among many others.

Olivier Pennetier of Symphysis used ArcView GIS with Digital Elevation Models (DEM) to create a map illustrating (2) the view orientation of the terrain, and (3) the site slope. Views to the west were favored by the client, so that any western aspect of the terrain was given a higher rating. Terrain slope was also computed based on the imported DEM, favoring areas with slope less than three degrees for lower construction costs.

A solar radiation plug-in called Solar Analyst was used to output solar irradiation incident on the terrain from user data inputs. These inputs included the time range (winter months), location of the site and clearness index (cloudiness at a particular location) based on gathered local solar radiation data. The solar irradiation level changes throughout the site based on the orientation and slope of the terrain, as well as any overshadowing by surrounding terrain (4).

A rating from 1 (worst in red) to 10 (best in green) was assigned to each of these maps. The maps were then combined to create a weighted map of the most desirable areas of the site in terms of slope, view aspect, and solar radiation potential. This "Desirability Index" map was later overlaid on the site in Google Earth, thus offering the ease of 3D terrain navigation to the client.

Interpretation and Next Steps

This 3D map gave the client informed options to select the location of the home. After walking the site numerous times, the client settled on a location precisely matching a high-ranking Desirability Index. Further analyses of building orientation and aesthetics continued to shape the residence.

5.2 SUNLIGHT ACCESS

Project type:
Residential towers

Location:
Wenjiang District, Sichuan, China

Design/modeling firm:
ZGF Architects LLP

Zoning laws in many countries and jurisdictions require solar access for a number of hours each day or minimum access on a given day, while others limit the solar shadowing of other parcels or buildings on a given day. This study analyzes the potential for solar access using sun paths and shading from all nearby buildings using an iterative solver.

Overview

The masterplanning phase involves making broad design moves that influence solar access, walkability, and many other factors for future residents. For this masterplan of an Eco-District, block sizes scaled to pedestrian movements needed to be reconciled with China's solar zoning laws that usually result in super-blocks with automobile-scaled rows of towers.

To optimize block sizes for pedestrians and create an interconnected, walkable grid, while respecting the local code for residential, mixed use and office buildings, the team set block sizes at 70 meters square. Tower dimensions were set at either 25 x 20m or 12 x 40m, two footprint sizes that allowed various placement of bedrooms to meet the requirement for solar access: one bedroom of every residence must get at least 2 hours of direct solar gain on the winter solstice. Laws governing the adjacency and separation of buildings meant that there could be no more than two towers per block.

Simulation

ZGF built a model of the site in Rhinocerous, and used Grasshopper and its iterative solver Galapagos to try different solutions for massing that optimized the development potential within these constraints.

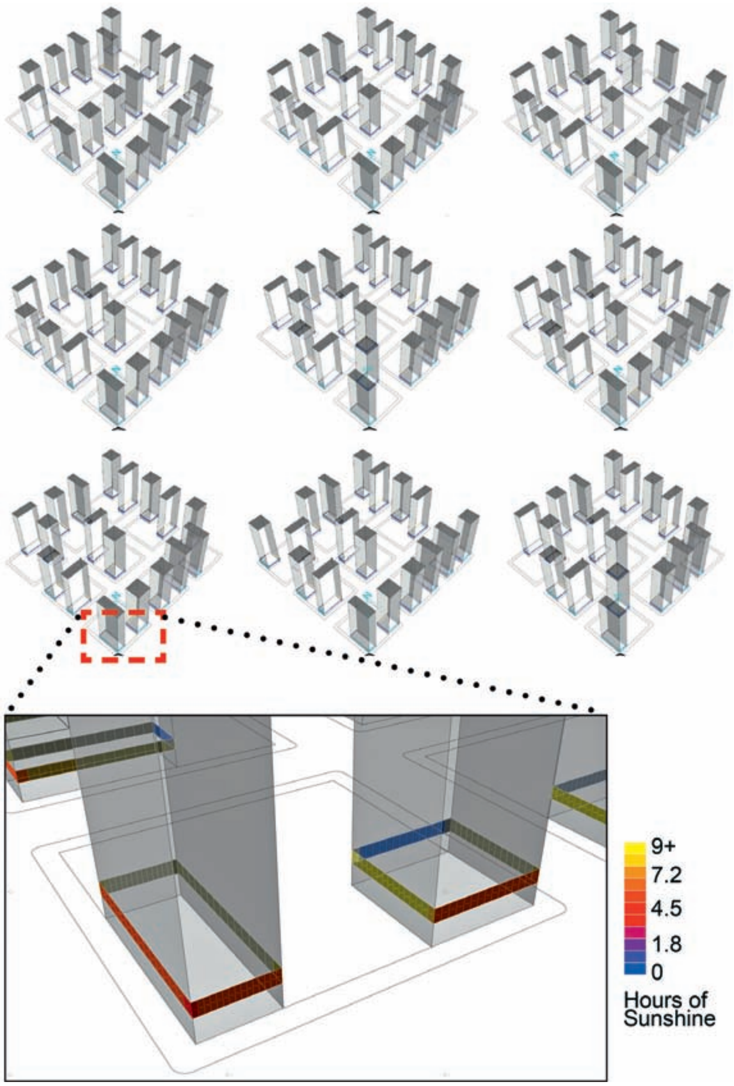
The elements that defined the massing of the towers were modeled parametrically in Grasshopper so that they could easily be manipulated, including the number of towers on the block, their width and depth, and their placement on the block. A script was created to randomly place either of the two tower sizes on each block and to check each potential solution by calculating the solar irradiation at the base of each tower, since the ground floor apartment is the worst case situation for each tower.

Geco software was used to export mesh geometry and analysis to Ecotect, which then performed the analysis and exported it back into Grasshopper. The data was then stored in a database and used as a fitness value for the Galapagos evolutionary solver using the minimum number of direct sun hours on December 21st.

The initial Geco/Ecotect interface took over a minute to analyze each iteration. With thousands of possible building placement options, the analysis would have been impractical without improving this technique.

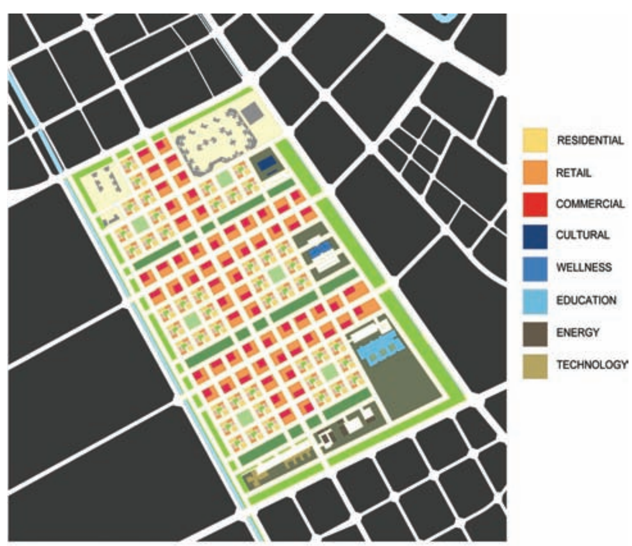
The team created a revised Grasshopper definition that duplicated the Ecotect solar access function, bringing the run-time down to less than 3 seconds per iteration. Galapagos was used to test each of the changeable geometric parameters defined by Grasshopper in nearly every possible combination. For each option, it analyzed solar exposure and ranked the top 50 solutions for the team to consider.

Over 10,000 iterations were studied, with no successful solution that permitted 2 hours of solar access at all apartment locations. While other solutions were possible, such as varying tower heights or the block dimensions, the team instead adopted the idea of creating a park within the center of every 9-block (3 x 3) group, reinforcing the idea of a more livable and walkable urban form. The iterative



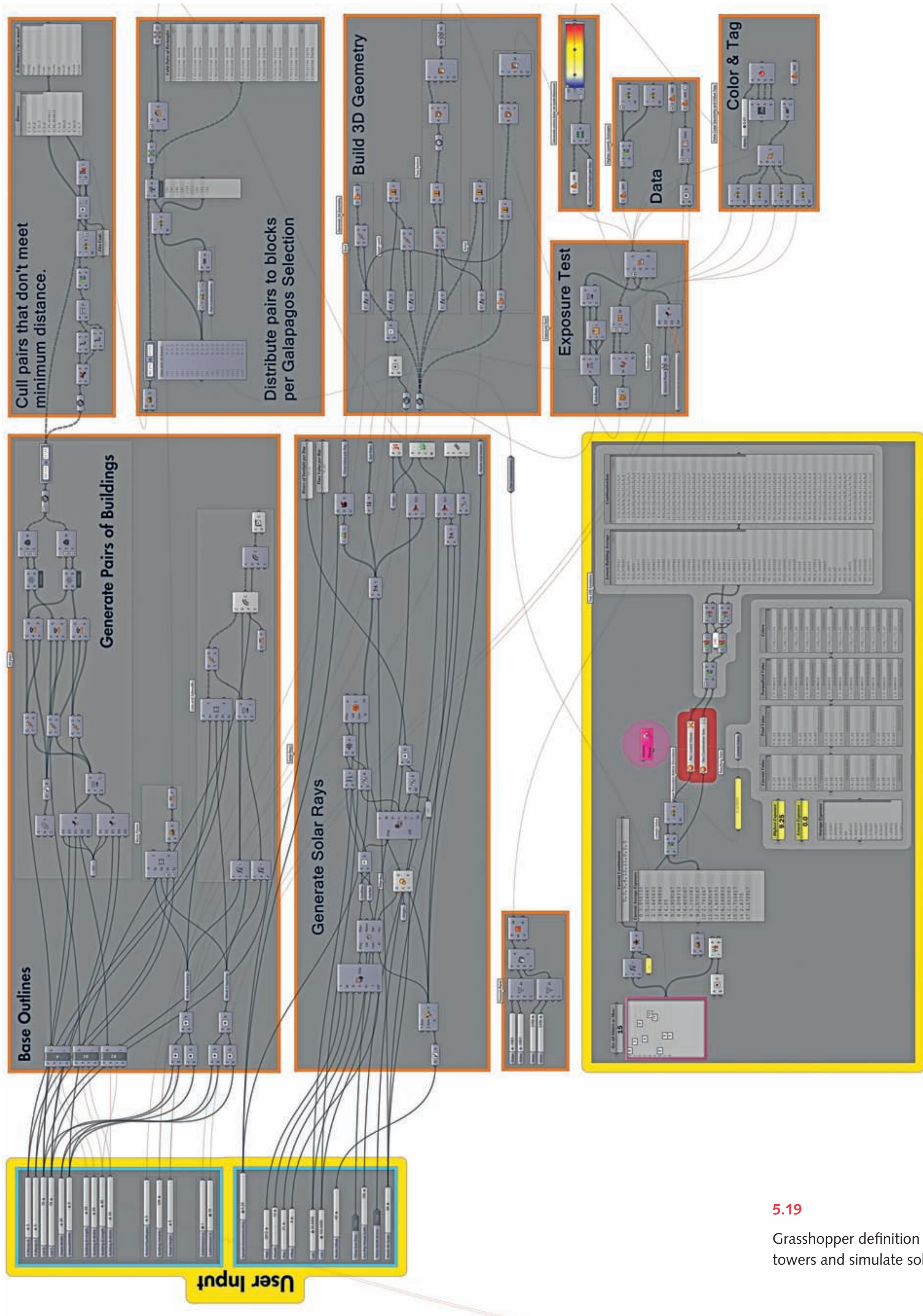
5.17

Nine massing options shown of the thousands that were tested. Detail of the testing method—sunlight hours at the base of each tower on each orientation.



5.18

Final masterplan that includes pedestrian-scale blocks of 70 m x 70 m, central parks, and achieves the solar access requirements.



5.19

Grasshopper definition to create towers and simulate solar access.

solver tackled this variation with far more success, and found many solutions that met the team's criteria for solar access and pedestrian scale. The final masterplan adopted the park as a central organizing idea.

Additional Studies

As a complement to this study, ZGF identified other aspects of the subtropical monsoon climate that could influence the urban design for this neighborhood, most significantly the hot, humid, and rainy summers, and predominant winds from north. This information was considered in concepts for open space micro-climates and building systems.

While this study was conducted within specific constraints and assumptions about building and block dimensions, the tool was further developed so that future design investigations could adjust and optimize many parameters, such as how to develop the greatest number of legal units within the smallest amount of land.

5.3 BASELINE ENERGY ANALYSIS

Determining baseline energy use at the beginning of a project can help the design team set reasonable goals and begin to choose appropriate strategies to meet those goals.

Project type:
Residential and hotel over retail

Location:
Vail, Colorado

Design/modeling firm:
Callison/Cobalt Engineers

Overview

As currently proposed, the Ever Vail project is a large, mixed-use masterplan that includes 5-story development with condominiums over retail, a new enclosed transit center, office space, a hotel, a children's recreational center, and other amenities. The Ever Vail masterplan achieved LEED for Neighborhood Development Platinum (Stage 2).

Cobalt Engineers of Vancouver, BC, were hired to work with Callison to explore all sustainable aspects and options for Ever Vail: energy, water, waste, and indoor environmental quality. The resulting 100+ page document contains specific information for the design of Ever Vail. Some of the initial research and energy studies are shown here.

Simulation

Since the town of Vail and project site are on the north side of Vail Mountain, the team first verified that the mountain itself did not block solar access to the site. Going farther, the team determined the actual hours of solar access throughout the year, reduced due to shading from the surrounding mountains, using Google Sketchup Pro and Google Earth. The solstices and the equinoxes were studied, representing extremes and averages. Corresponding sunrise and sunset times were derived from IES VE

5.20

Rendering looking southwest.

Note: Photos, renderings, and data are courtesy of Vail Resorts Development Company and may not be reproduced without permission.

5.21

Actual sunrise and sunset times due to surrounding terrain.

Note: Photos, renderings, and data are courtesy of Vail Resorts Development Company and may not be reproduced without permission.

	Sunrise	Duration of morning terrain shadow (minutes)	Period of full solar exposure on site	Duration of afternoon terrain shadow (minutes)	Sunset
21-Mar	6:17	9	6:26 - 17:23	51	18:14
21-Jun	4:45	48	5:33 - 18:17	76	19:33
21-Sep	6:00	13	6:13 - 17:08	50	17:58
21-Dec	7:31	61	8:32 - 15:32	70	16:42

5.22

Available EnergyPlus weather files, using Google Earth.

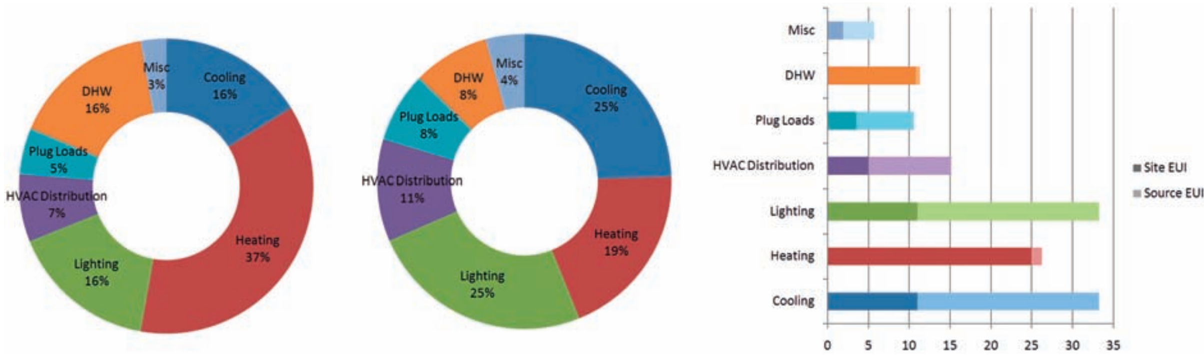
Note: Photos, renderings, and data are courtesy of Vail Resorts Development Company and may not be reproduced without permission.

calculations, with effective solar access found to be reduced by two hours on the winter solstice. This information informed some of the early energy modeling.

Initial studies of possible site configurations included goals for optimizing views and solar orientations. Low winter sun angles and dense, walkable, 5-story development precluded each residence from being entirely passively heated.

Target-Finder was consulted to provide a 2030 Challenge Target for the entire build-out, including structured parking, of 51 kBtu/ft^2/yr Site EUI or 110 Source EUI. Each typology was also run separately for 2030 Challenge compliance, with the hotel targeting 41kBtu Site EUI or 89 Source EUI as shown in Figure 5.20.

The next study required finding the most appropriate weather file for early energy analysis. The EPW weather data layer for Google Earth can be found on the EERE weather file website. While a weather station did exist in Vail (+8100 feet elevation), it contained only a few years of raw data. Nearby weather files are in Eagle (29 miles away, 6470 ft of elevation), Leadville (29 miles, 9926 ft) and Aspen (39 miles, 7750 ft). While Eagle is closer, it lies in a more open area; Leadville is in a north–south mountainous area; since Aspen has the most similar adjacent terrain and elevation, it was judged the most appropriate.



Results for Estimated Energy Use			
Energy	**Design**	**Target**	**Median Building**
Energy Performance Rating (1-100)	N/A	97	50
Energy Reduction (%)	N/A	60	0
Source Energy Use Intensity (kBtu/Sq. Ft./yr)	N/A	110	274
Site Energy Use Intensity (kBtu/Sq. Ft./yr)	N/A	51	127
Total Annual Source Energy (kBtu)	N/A	85,454,353	213,635,882
Total Annual Site Energy (kBtu)	N/A	39,662,845	99,157,112
Total Annual Energy Cost ($)	N/A	$ 547,755	$ 1,369,388
Pollution Emissions			
CO2-eq Emissions (metric tons/year)	N/A	5,969	14,921
CO2-eq Emissions Reduction (%)	N/A	60%	0%

5.23

Green Building Studio (Autodesk) shoebox energy model results showing relative energy uses and carbon intensities. The pie charts show carbon contribution when calculating site (left) and source (middle) energy. The bar graph shows how deceptive site energy calculations can be when considering overall contribution of carbon to the atmosphere.

Note: Photos, renderings, and data are courtesy of Vail Resorts Development Company and may not be reproduced without permission.

5.24

Target-Finder goals for 60% Energy Use Intensity reduction.

Source: https://www.energystar.gov/index.cfm?fuseaction=target_finder.

While Vail is an extremely cold climate, the skies are clear and sunny enough to create cooling loads nearly year-round. Anecdotally, the project team learned that many area residences experience thermal discomfort even in the winter from overheating due to highly glazed façades.

In fact, the Green Building Studio baseline analysis shows that source energy required for cooling is greater than for heating on an annual basis. This is due to cooling generally being provided using electricity, which has a source penalty 3.4 times the rate for heating provided by gas. Figure 5.23 shows the site and source energy use.

In addition to super-insulation, triple glazing, and natural ventilation, several other strategies were considered to reduce source EUI and cooling loads. While a low solar heat gain coefficient (SHGC) glazing and fixed shading would decrease summertime cooling, it would increase wintertime heating, and would not use the plentiful solar resource. A better-performing option was studied, using high SHGC glazing and automatic external operable shades to control overheating and minimize cooling loads. The team determined that building geometry could be used to block summer heat gains while collecting winter heat gains; a later study of one massing option is shown in Case Study 7.3.

To further reduce source EUI, the team studied on-site electricity generation, such as from photovoltaics or a Combined Heat and Power (CHP) plant. CHP would generate electricity plus waste heat that could be used for absorption chillers or domestic hot water. A biomass plant was also studied, as well as micro-hydro and other on-site electricity-producing renewable energy sources.

Cobalt Engineers used IES VE Pro to run a quick analysis to determine baseline energy end uses based on code-compliant construction. This study was used to create an overall picture of energy uses on site, and allowed the team to estimate the energy advantages of thermal loops connecting the buildings. The study required an understanding of estimated monthly occupancy, shown in Figure 5.26.

5.25

Conceptual site plan showing district energy diagram.

Note: Photos, renderings, and data are courtesy of Vail Resorts Development Company and may not be reproduced without permission.

5.26

Projected monthly occupancy by typology.

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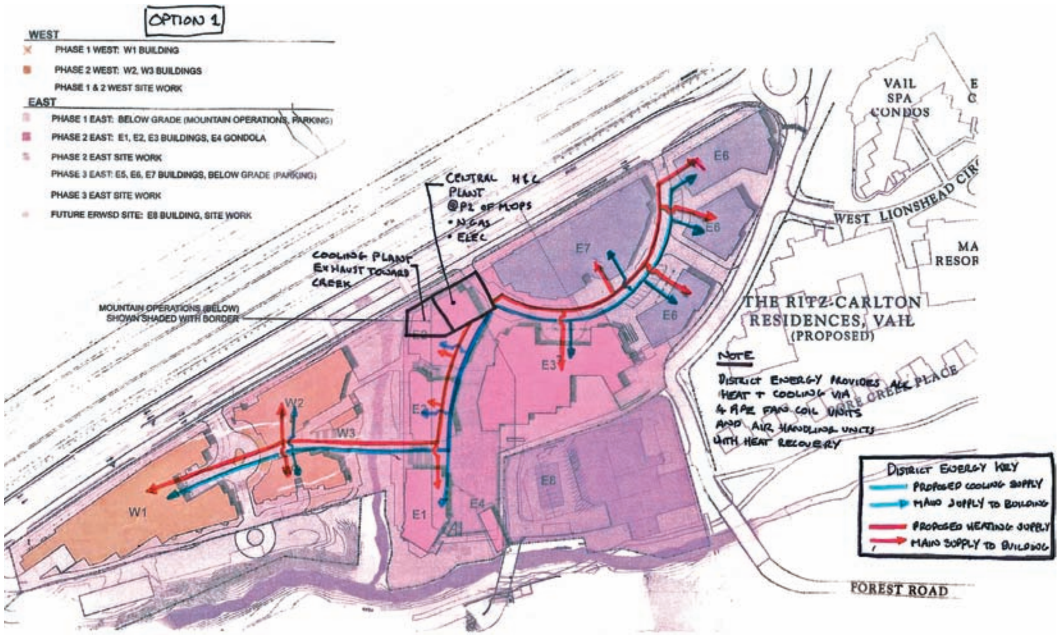
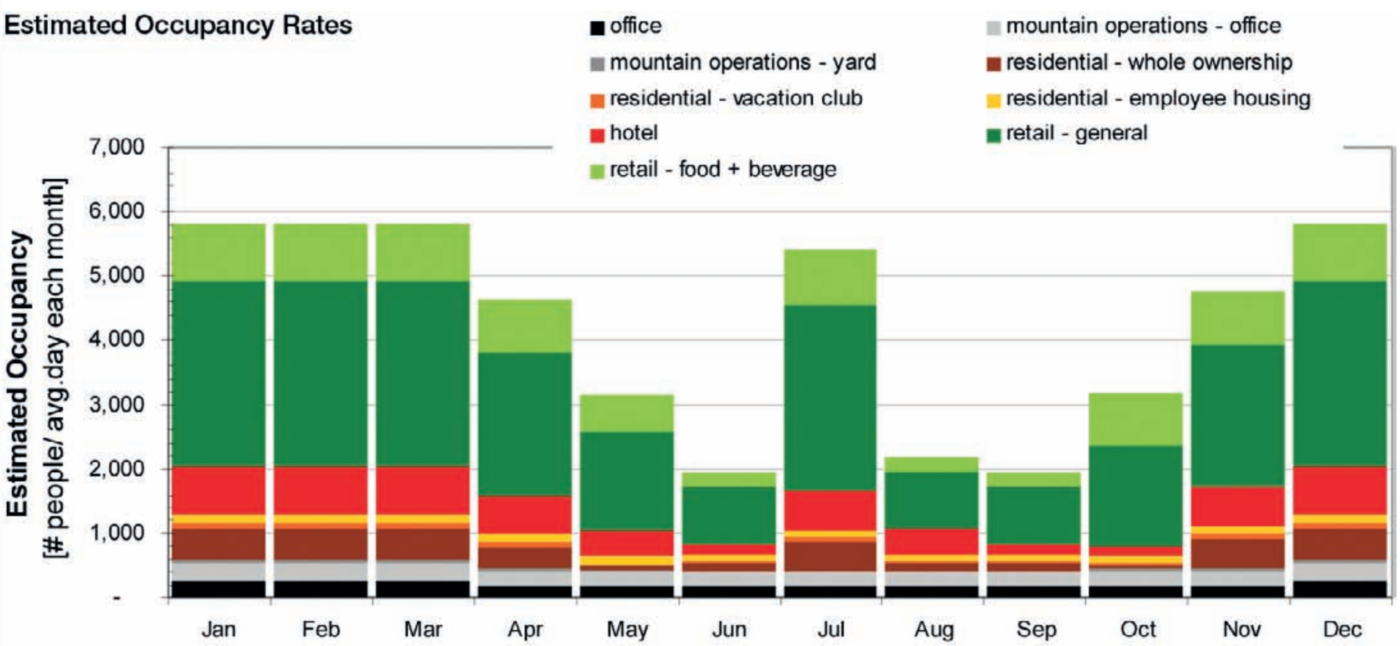




The town of Vail zoning code discouraged photovoltaics due to perceived glare issues viewed from the mountain to the south. In addition, roof-mounted PV panels in snowy climates present unique challenges due to snow accumulation, sloughing and water penetration issues, so the team studied precedents early in the process. Solar thermal was also planned as part of the project, with the benefit of panels being able to melt any accumulated snow. They were considered for producing energy for domestic hot water, some space heating, as well as powering absorption chillers during cooling periods.

Each of these studies was used to provide a masterplanning level of detail to determine optimum site layouts, roof slopes for renewable energy, and energy goals.

5.4 MASSING ENERGY ANALYSIS

Massing studies can be informed with early shoebox energy modeling using the correct typology, representative geometry, and default inputs and schedules from an energy modeling software.

Project type:
3-story office building

Location:
Seattle, Washington

Design/modeling firm:
ZGF Architects LLP

Overview

During the three-month competition phase for the Federal Center South (Building 1202), the design-build team was interested in the effect of orientation on annual energy use and mechanical sizing in Seattle's overcast climate. In addition to producing a quality design, the competition required that design teams guarantee cost and performance, meeting both the GSA's established budget and the ambitious energy target of 30% better than ASHRAE 90.1–2007, or an effective EUI at or below 27.6 kbtu/ft^2/year. ZGF's project team won the competition with a completed construction in 2012.

A complex geometric model with detailed inputs was beyond reasonable time and cost at this early phase, especially since there were numerous design concepts to analyze. Since each massing concept proposed a linear office bar building, the architects simply wanted to know the impact of orientation on its energy performance, as well as the heating and cooling loads which would dictate the mechanical equipment sizing. The analysis was instrumental in tightening up the early orientation of the massing diagrams, and the built project uses a nearly identical layout to the one shown in Figure 5.27.

Simulation

The team knew that a 3-story building with long office floor plates was likely to be the best option based on the program and the zoning code. To set the width of the typical floor plates, a simple daylight

5.27

View of final design from northeast.

5.28

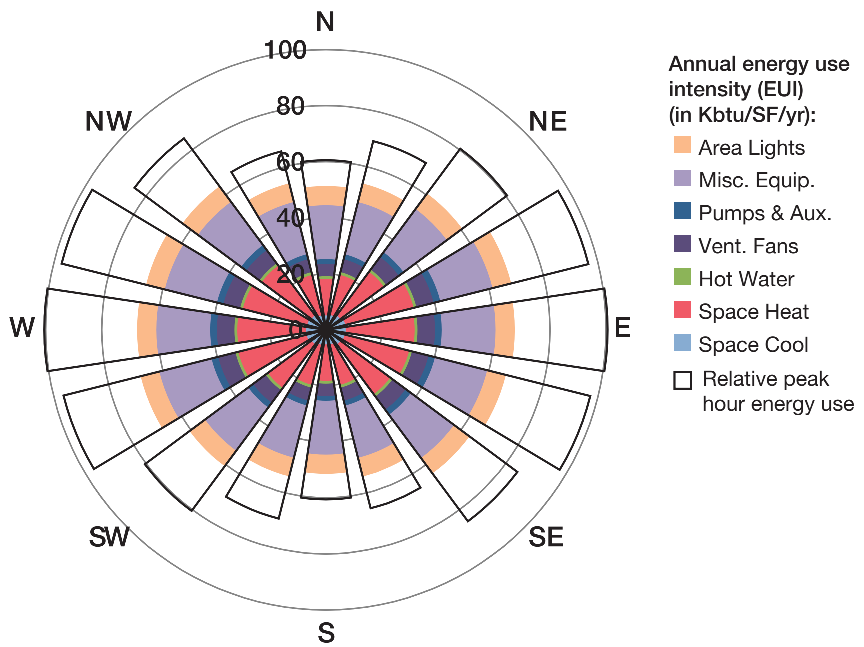
Peak loads and annual energy use, diagrammed based on orientation.

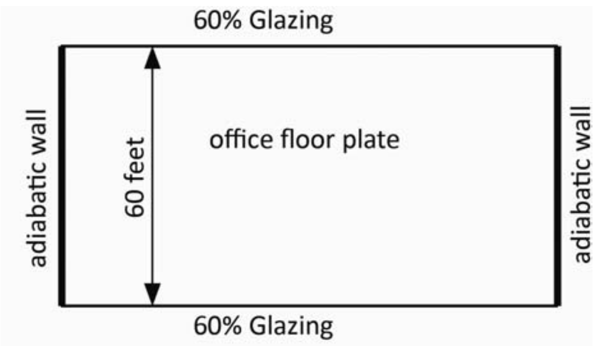
5.29

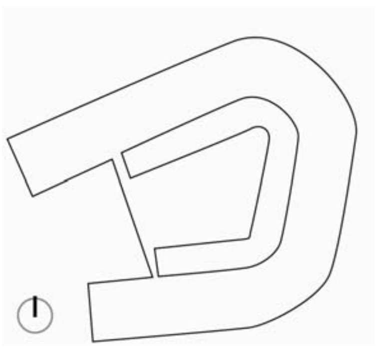
Typical office bay that was used for orientation shoebox modeling.

5.30

Resulting floor plate design.







model was performed. The results generally indicated that a 60′ width would be ideal to get a daylight factor of 2% throughout the majority of the floor plate with 8′ of continuous glazing (from 2′6″ sill to 10′6″) on both sides.

This floor plate was created using the eQuest Schematic Design Wizard, which automates many of the energy modeling inputs using standard office assumptions. Since the length of the office building was still being studied, a representative portion of the length was modeled as a shoebox model. The two unglazed ends walls were set to be nearly adiabatic, using extremely high insulation values, so little conduction energy would transfer through them.

The model was run at all orientations in increments of 22.5°. The results were then graphed to show the relative annual and peak loads based on the model. Typical glazing (double pane low-E, with eQuest default values for U and SHGC) and code wall assemblies were included.

The study shows that both peak and annual loads can be reduced by orienting the bar buildings in an east–west direction. In fact, the peak cooling and ventilation loads which determine mechanical plant size and cost were estimated to be 36% lower with the proper orientation.

6
Glazing Properties

Expansive glazing is the hallmark of twentieth-century architecture. Modern float glass and other technology have expanded the role of glass into a complete cladding material. Interiors are visually connected to exteriors even while protected from wind, rain, and outdoor temperatures. Large panes of glass evoke the ideal of transparent democracy, heighten retail displays, and enable buildings to reflect the changing patterns and colors of the sky above.

While in previous centuries, windows were sources of controlled light and heat for buildings, many architects in the mid-twentieth century cast aside the lessons of the past, leaning on their engineers to provide energy-intensive indoor comfort.

A combination of window technology and energy consciousness has reversed the trend. Two panes of glass with a sealed airspace between them, called an insulated glazing unit (IGU), double the thermal resistance of single glazing; with low-e coatings, triple the insulation value is now standard.

In addition to better window technology, architects are re-learning how to size windows for appropriate light and heat again. Façades with a glazing percentage of 30–40% provide optimal energy use over a variety of typologies, and most codes use this range as the upper limit for prescriptive energy compliance.

Designing the right quantity, location, orientation, and type of glazing is the most important aspect of energy use on most projects, affecting comfort (Chapter 3), solar loads (Chapter 7), daylight (Chapter 8), natural ventilation (Chapter 9), and overall energy use (Chapter 10). To maximize the effectiveness of each of these strategies, an understanding of the greenhouse effect and glazing properties is essential.

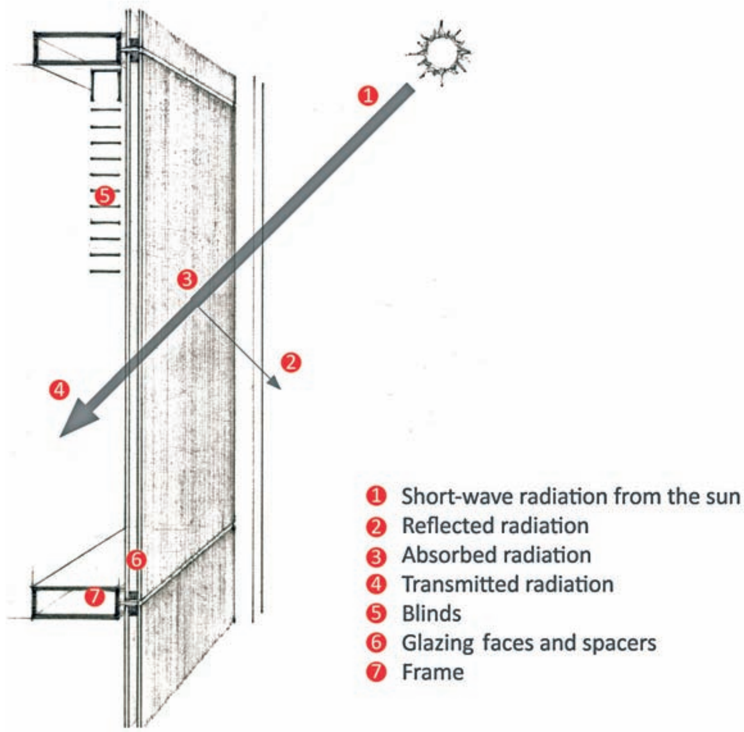
THE GREENHOUSE EFFECT

A window can act as a net heat source when conductive, radiant, and infiltration losses through the window and adjacent wall are less than the solar energy gained through it. This is called the greenhouse effect, literally taken from how greenhouses heat up even with small amounts of solar energy.

The greenhouse effect occurs because glass is transparent to the sun's short-wave radiation but opaque to long-wave radiation. Once the sun's energy is transmitted through glass into a building and absorbed by the interior materials, it is re-radiated as long-wave, now trapped by the glazing. If the space is reasonably airtight, the long-wave radiation quickly heats up the surfaces and air within a space, resulting in high interior temperatures. A car's super-heated interior on a warm day is a simple example of the greenhouse effect.

When the sun's short-wave energy hits the glass, all of it is reflected, absorbed, or transmitted through the glass. The angle at which the window receives the sun's energy is called the angle of incidence, and affects how much light and heat is reflected. Some solar energy is absorbed by the glass, coatings, frits or films. Some of this absorbed energy re-radiates as long waves outward, and the rest radiates inward, adding to heat gain. The remaining solar light and heat are transmitted through the glass.

Interior blinds may block the solar beams from causing direct thermal or visual discomfort. However, once heat has been transmitted through the glass, the majority of it is trapped within the building due to the greenhouse effect. Interior blinds cause the space between the glazing and blinds to super-heat,



6.1

Solar energy interacting with window properties.

Source: Amal Kissoondyal.

reducing the cooling load slightly by forcing some heat out through the glass via conduction. Most of the heat, though, becomes a cooling load.

Each glazing face in an IGU is numbered for reference, with the #1 surface facing the outside and #4 facing inside. Glazing products contain coatings applied to the glass to tune it for a specific purpose, usually to the #2 or #3 face. Spacers around the perimeter of the glazing maintain spacing and absorb moisture. An IGU is held in place by a frame, made of nearly any material, or structural silicone is used for a frameless look.

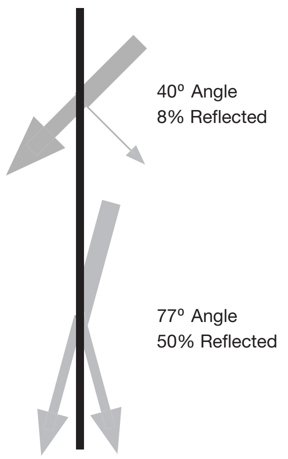
VARIOUS GLAZING PROPERTIES

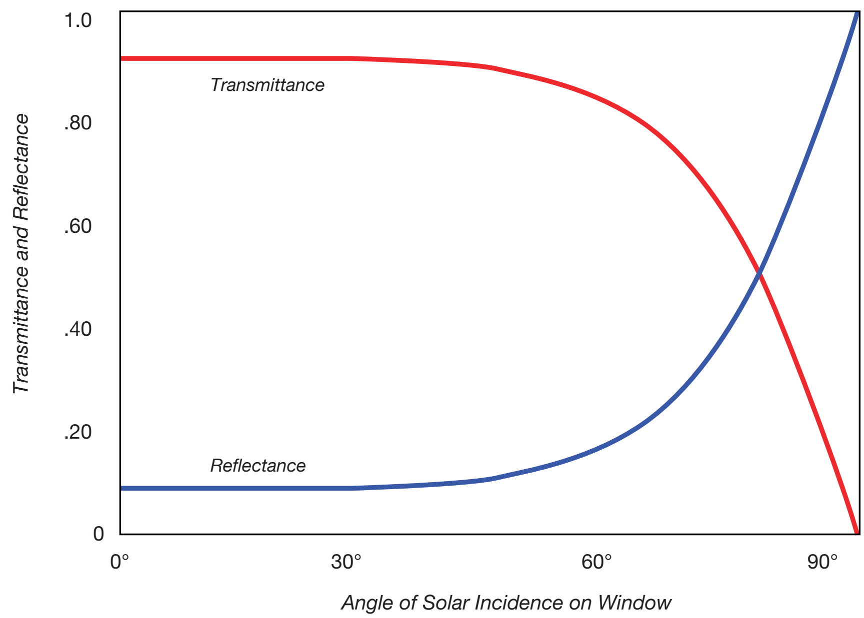
Glazing properties of interest in early design simulation include: the solar heat gain coefficient (SHGC), the visible transmittance (Tvis), and thermal conductivity (U-value). The SHGC is important for controlling solar gain (see Chapter 7), the Tvis for daylighting (see Chapter 8), and the U-value for conductive heat gains and losses (see Chapter 10). Operability is also an important consideration, primarily affecting airflow (see Chapter 9), but also generally reducing the overall insulation value. A low U-value and high Tvis are generally preferable for all windows, while the desired SHGC is based on the project team's chosen solar design strategy, covered in Chapter 7.

These window properties are readily available from manufacturers and may be explored in software such as Optics from Lawrence Berkeley National Labs (LBNL). A nearly infinite variety of colors and window properties is possible. Combinations include two varying panes of glass, plus spacers, coatings, and frame material, thickness, style, translucency, and operability.

Coatings are applied to glass to enhance properties. Most coatings are applied only to the inside faces (#2 and #3) of double-glazed windows for protection, referred to as soft coatings. Hard coatings can be applied to exterior glazing faces (#1 and #4), but are slightly less effective and can be scratched during cleaning and by sharp objects. Hard coatings can be used to retrofit existing glazing and to improve properties on advanced glazing products.

The National Fenestration Rating Council (NFRC) oversees the standards and ratings process for US window products, using a combination of simulated and physical testing. The standard NFRC window





label includes SHGC, Tvis, U-value, air leakage, and condensation resistance on it. The US Energy Star program requires NFRC-rated thresholds for energy efficiency rebates.

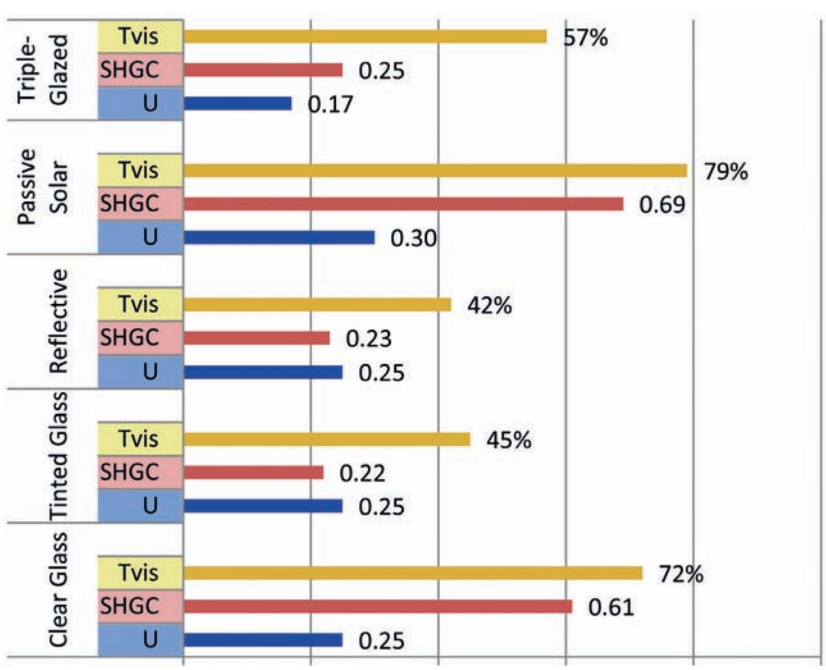
Visible Transmittance (Tvis)

Visible transmittance (Tvis) is the percentage of visible light that passes through a product. An opaque material has a Tvis of 0, with most double-glazed windows having between .25 and .75. Low-iron glass, which contains less iron impurities and is slightly less green, achieves the highest Tvis, around .94 per pane or .88 per IGU. Coatings, glass color, and applied frits or patterns also affect Tvis.

6.2 and 6.3

Reflectance for most glazing is around 8% for angles up to 40°. At 75°, nearly half the light and heat are reflected, while at 85° nearly 80% is reflected illustrating why shading is less necessary to control high-angle sun. Glass and coating properties further decrease the amount of transmitted light and heat. These diagrams are equally applicable in plan or section view since they consider the three-dimensional sun angle.

Source: ASHRAE.



6.4

Glazing properties from some widely manufactured insulated glazing units (IGUs).

Source: Courtesy of Callison. Chart based on ©ASHRAE Handbook of Fundamentals (2005), 31.20.

Solar Heat Gain Coefficient (SHGC)

The solar heat gain coefficient (SHGC) is the fraction of the incident solar radiation transmitted through a window plus the portion absorbed and subsequently released inward. Reflectance plays a large role. An SHGC of 0 refers to an opaque object, while most double-glazed windows have between .30 and .80 SHGC.

The SHGC from a window manufacturer is a single number that averages the window performance of a whole assembly through an entire year. It includes any heat blocked by the frame depth, and by the outward-radiating component of energy absorbed by the glass. It is accurate enough for use in conceptual energy estimates. For more detailed studies, the angle of incidence of irradiation on the glazing needs to be calculated to understand the amount of reflected light and heat, and the portion blocked by the frame depth.

Atrium skylight glazing usually has a lower SHGC than vertical glazing, since it receives more of the sun's energy, and does not need a high Tvis in order to provide lighting. Skylight assemblies used in large retail environments and warehouses are often translucent to diffuse light and create more consistent lighting levels.

The ratio of light (Tvis) to solar gain (SHGC) is called the light to solar gain (LSG) ratio. Since we only see light between 380 (violet) and 680 (red) nanometers in length, roughly 47% of solar power is in the visible spectrum, with less than 3% in the ultraviolet and the remaining 50% in the infrared range.

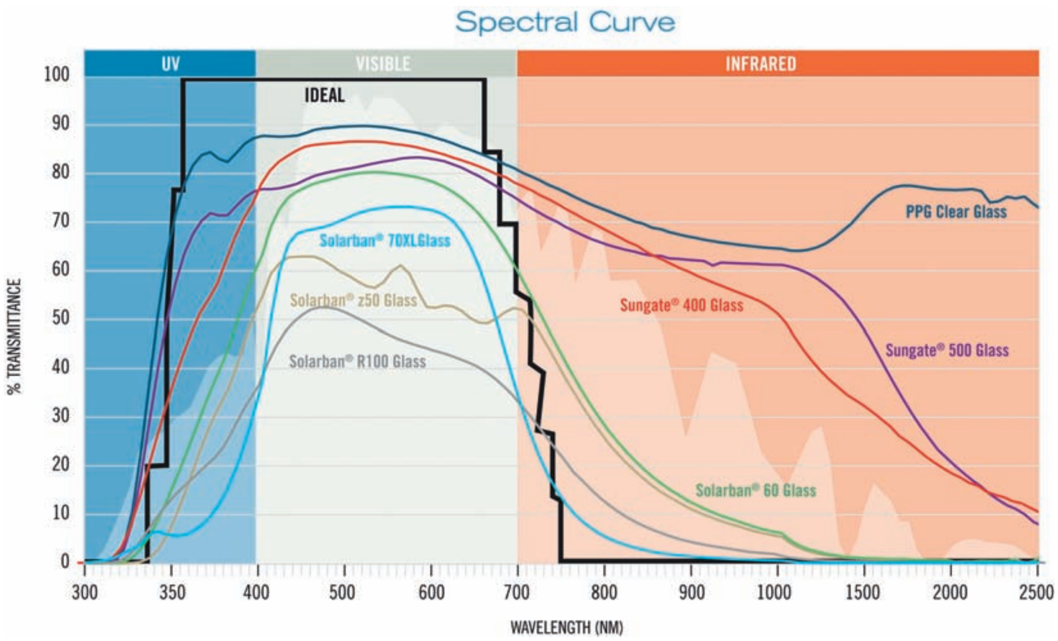
Spectrally Selective Coatings

Spectrally selective coatings reflect the infrared and ultraviolet light outside the visible spectrum. Because of this, they can achieve a high LSG—2 or better—which is very useful in warm or hot climates. Project teams designing for passive solar prefer an LSG near 1. Figure 6.5 illustrates the wavelengths that some glazed products are able to block.

As an unintended consequence, outdoor areas near highly glazed buildings with reflective glazing, and especially spectrally selective glazing, may receive the invisible reflected portion of the sun's heat, affecting vegetation and public spaces. In extreme examples, this can actually cause burns, such as at the Vdara Hotel in Las Vegas.

U-Value

A U-value measures the conductance of heat through a material or assembly. For glazed products in the USA, it refers to the entire window assembly, including the frame. Occasionally literature will list a center of glass (COG) U-value, since the glazed portion almost always performs better than the frame and spacers. Most building codes prescribe the assembly value, however. Conduction through glazing is not the same at all temperatures, so products can be rated for a Summer and Winter U-value.



6.5

Spectrally selective coatings allow glazing products to reflect solar irradiation outside the visible spectrum without significantly reducing visible light transmittance. This allows low-SHGC products with high Tvis.

Source: Courtesy of PPG Industries.

Low-Emissivity Coatings

Low-emissivity coatings (called low-e) are often applied to one of the inside faces of double-glazed assemblies to improve the U-value. The coating reduces long-wave, infrared radiant heat transfer between the panes, keeping heat within the building in the winter and keeping it out in the summer.

Reflectance

Reflectance plays a large role in lowering a SHGC. Reflectance for most IGUs is around 8%, but highly reflective (15% to 30% or more) or anti-reflective coatings (around 1%) can be applied. Spectrally selective coatings reflect mostly invisible light. Retailers prefer anti-reflective glass to increase visibility deep into a store. Lobbies of many office buildings incorporate anti-reflective glass for transparency as well.

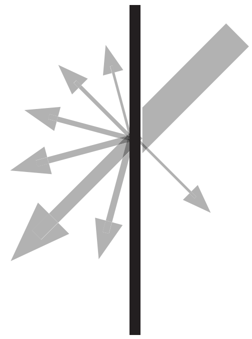
TRANSLUCENCY AND SPECIALITY PRODUCTS

Areas of glazing have a significant effect on energy use in buildings, so a great deal of research has gone into creating a wide variety of products to give the designer many options to control light and heat.

A product is considered *translucent* if it diffuses some transmitted light, obscuring the view and distributing light more evenly through a space. Diffused light reduces the potential for glare from direct sunlight. However, translucent products may themselves glow more brightly than indoor light levels, causing glare as discussed in Chapter 8.

Some innovative glazing products have properties that are worth considering on low-energy projects:

- Some glazing products can change color, SHGC, Tvis, and other properties using electro-chromatics or other technologies, although prices still preclude use on most projects.
- Vision, spandrel glass, or skylight glass can be laminated with thin-film photovoltaics to generate small amounts of electricity. Thin-film will effectively increase the SHGC of the glass, causing it to shade the interior, though the glass absorbs heat as a consequence. Vertical glazing generally has a non-ideal orientation for solar harvesting, but skylights can be oriented for maximum energy harvesting.



6.6

Translucent materials transmit some light and heat directly, and diffuse the rest of the transmitted light. In most cases, the diffused light is more concentrated around the directly transmitted light.

- Solar thermal hot water can be located behind glass wall panels within a curtain wall or window wall system.
- Ceramic frits can be applied to glass in a variety of densities and colors to reduce solar gain while maintaining views. Frits cause additional heat to be absorbed by the glass, much of which is re-radiated into the building. They can also be a source of glare in direct sunlight if the inside face is too light. Fritted glass can also deter birds from flying into glass buildings.
- Translucent phase change materials (PCMs) can be inserted behind or between glass layers for thermal storage.
- Angular selective solar control products allow light at some angles while blocking light at other angles. While no commercial products are yet available, this could be a promising avenue for future research.
- Some glazing products contain internal louvers that block certain angles of direct sunlight while admitting diffuse daylight, with the louvers designed for a specific latitude and climate. These products are used in Europe but are not yet popular in the USA.

SINGLE, DOUBLE, AND TRIPLE GLAZING

Sheet glass as a material does not provide much insulation value. However, every transition from a solid (glass) to air increases the resistance value due to the "air film" against the glass. An air film is a layer of air held relatively motionless by friction with the solid, providing measurable insulation value. Air films outside a building are averaged at R-.17, and air films that experience very little wind effect (indoors) are averaged at R-.60 to R-.70. Summing the R values of indoor and outdoor air films plus a single sheet of glass totals around the center of glass (COG) R-1.

Double-glazed units with an air space have an insulation value of around COG R-2, with the resistance of the air between the panes being nearly R-1. The ideal distance between panes is around 1/2" to 3/4"; beyond this distance, air convection begins cycling between the panes, transferring heat and reducing thermal resistance.

Adding a low-e coating can increase performance to around COG R-3 (U = .33). To increase resistance further, a gas such as Argon can be used instead of air between the panes, increasing performance to around COG R-4 (U = .25).

Triple-glazed assemblies utilize three panes and two air spaces and often include at least two low-e coatings. They are infrequently used due to their additional weight, thickness, and cost, though with more widespread use costs are expected to come down. Most window frames and curtain walls currently only allow the thickness for double-glazed IGUs, so manufacturers often modify existing window framing systems to accommodate triple-glazed IGUs. To meet Passivhaus criteria, triple-glazed IGUs are essential.

FRAMES AND OPERABILITY

Glazing assemblies can be separated into several types based on frame: windows, window wall, curtain wall, and skylights. Each of these products may use the same basic IGU.

6.7

The window selection for the Net Zero Energy Bullitt Center in Seattle involved finding a high-performance window with automatic operability. The German window manufacturer Schuco provided a window design that minimized thermal bridging through the aluminum frame and opens 3″ to 4″ parallel to the building façade, reducing differential wear on the gaskets and airflow through the frame. Tvis = .60 and U = .25 overall, including operable lites.

Source: Photograph © Kjell Anderson.

Windows are standard products that are sold and rated as a unit. A window wall is an assembly that usually spans from one floor to the underside of the floor above. A curtain wall often continuously covers an entire façade, making infiltration control easier. In curtain walls, insulated spandrel panels or shadow boxes replace vision glazing to control the glazing percentage and resulting energy performance. Spandrels can also incorporate photovoltaics, solar thermal collectors, air intakes, or natural ventilation louvers.

Frames and mullions are thermally the worst-performing aspects of glazing assemblies. While non-metal frames such as fiberglass are adequate insulators, aluminum frames are poor insulators. In general, reducing the quantity of mullions increases the thermal performance of a window system. As an example, an IGU with a COG rating of U = .25 may become a U = .45 overall assembly with a thermally-broken aluminum frame, transferring nearly twice as much thermal energy.

IGUs contain spacers at the perimeter to maintain the air gap distance between panes, even under wind loads. Spacers are thermal bridges between panes, transferring heat. Spacers also absorb moisture that may slowly leak into the assembly.

Operable windows use more frame material, and have worse U-values than similar fixed products. However, when they provide fresh air or cooling, the worse thermal performance is generally offset by reduced overall energy use, which can be tested with design simulation software.

CONCLUSION

Technological advances have made glazing an integral part of buildings, becoming the only cladding material used on some buildings. However, glazing was overused in the twentieth century. Even with constant advances in performance, its poor thermal insulation value means that design teams on low-energy buildings use glazing selectively to provide the right amount of light and heat during each season. The choice of a glazing product involves all aspects of energy performance of a building —heat gain and shading, daylighting, operability, and envelope conduction.

7

Solar Irradiation and Thermal Storage

I have nothing to ask but that you would remove to the other side, that you may not, by intercepting the sunshine, take from me what you cannot give.

—Diogenes

The intense warmth of sunshine can make a cold, wintry day pleasant, or cause one to seek shade and a breeze on a hot day. In buildings, solar energy creates a local, intense heat load that can be used for space heating if it is spread out spatially and through time. Often, it is also the largest contributor to peak cooling loads, and can cause localized discomfort, as discussed in Chapter 3.

Passively heated buildings are a staple in sustainable architecture theory, but the measured use of passive solar energy is not well understood by most architects. The fact that the US Government's Energy Star program only offers rebates for low-SHGC glazing (to block the sun's energy) is a testament to the poor understanding and use of solar heating, shading, and thermal storage in most climates. Many low-energy buildings, such as those designed to Passivhaus standards, use high-SHGC glazing and orientation to reduce energy use.

Light and heat are inseparable. Most shading simulations will be conducted alongside daylighting and glare studies, covered in Chapter 8. Solar design and thermal storage are also inseparable. Thermal mass or storage can spread solar heat gains over 24 hours, while buildings with no storage may need to be heated and cooled within the same day.

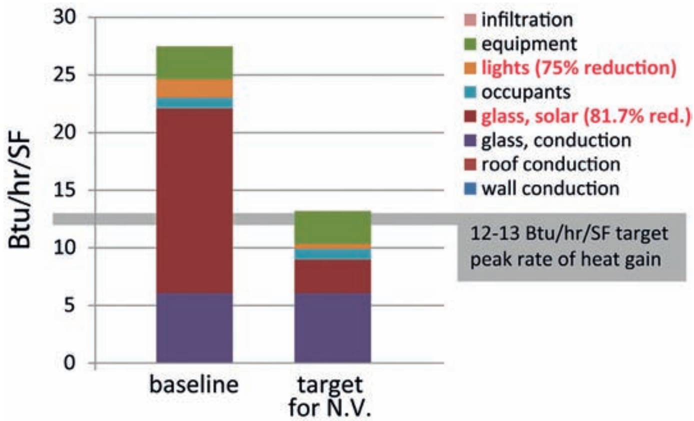
While this chapter uses the term shading to refer to allowing or reducing heat gains, the most effective strategies to reduce unwanted solar gain are window orientation, sizing, and integral building geometry that provides shade. Purpose-designed shading is a secondary refinement since it is less effective and more costly.

Good design begins by establishing a solar design strategy and solar load targets, and then crafting a building to achieve the targets. This chapter addresses simulations of solar energy on buildings, as well as using thermal storage to delay or mitigate heating and cooling needs. Solar access and shading strategies are covered first, followed by solar measurement, shading, and thermal storage. The term *thermal storage* will be used instead of the more common term *thermal mass*, to include the energy storage capabilities of phase change materials (PCMs).

SOLAR DESIGN STRATEGIES

To create a design that effectively harnesses the sun's heat, the project team needs to develop a strategy on how solar energy will be used in each programmatic space. The strategy expresses the chosen balance between allowing desired solar heat gains and excluding unwanted heat gains. Strategies include solar heating and shading with or without thermal mass, peak load reduction, shading only, or using an unconditioned sunspace to trap solar energy for heating or for dispersal.

If reducing source energy use has been set as a project goal, reducing cooling loads that use off-site electricity are roughly three times more effective than reducing heating loads that will use natural gas, as explained in Chapter 5 on planning and goal-setting. Options include:

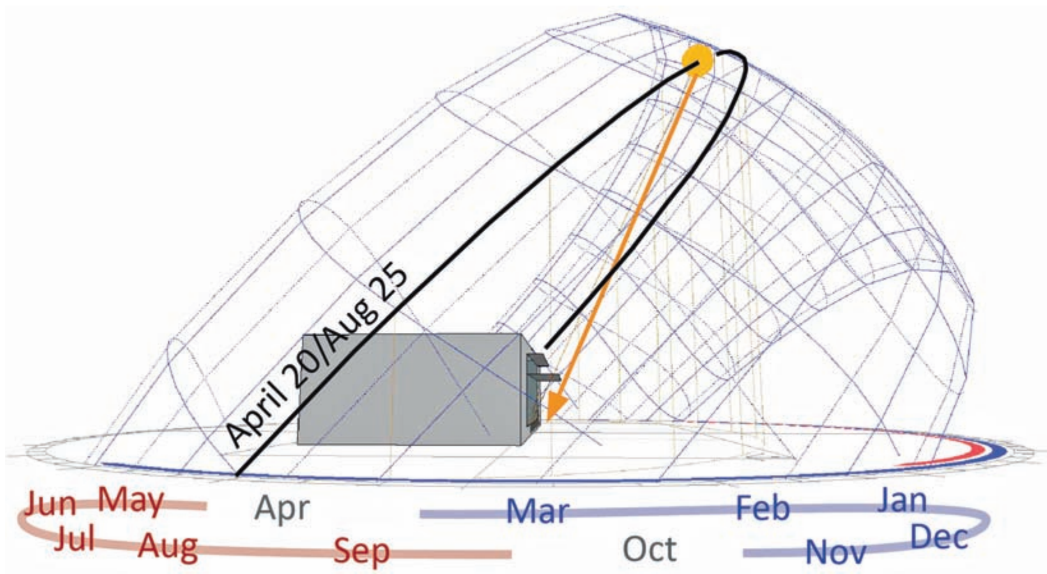


7.1

A lab building at the University of Washington used an eQuest energy model to simulate peak cooling load conditions. In order to eliminate a mechanical cooling system and use only natural ventilation for cooling, peaks loads needed to be reduced by 50% from a baseline. The project team was able to test many options, finding a balance that met the target by reducing glazing percentage, using windows with different properties, and providing shading during peak periods.

Source: Courtesy of ZGF Architects.

1. *Solar heating and shading with thermal storage*. In most climates, orientation and shading need to be designed to provide a balance between heating requirements in winter and overheating in summer. With thermal storage, several hours of daytime solar gains can be balanced against night-time heat losses during cold periods. During the hot season, excess solar gain can be balanced against night-time cooling. This approach often uses higher-SHGC glazing (.5 or higher), especially in combination with operable shading.
2. *Solar heating and shading with no thermal storage*. Buildings cannot use most solar gain advantageously without thermal storage in many climates. Solar gains over the course of the day are exacerbated by higher daytime occupancy and equipment use. Excess daytime heat loads are often balanced with energy-intensive mechanical cooling, and night-time losses are often balanced with mechanical heating. The best strategies without thermal storage usually involve low SHGC glazing (such as .2 to .4) to minimize this daily solar gain cycle.
3. *Peak load reduction*. Peak loads drive mechanical system selection, duct sizes and airflows, and the resulting cost. Solar loads tend to make up a large percentage of the overall peak cooling loads in many climates. Efficient cooling systems such as natural ventilation and radiant cooling require the architecture and façade to limit the peak cooling loads. The designer is looking for the sweet spot where daylighting reduces electric lighting use and associated heat, while fenestration orientation and shading reduce solar loads. Orienting and sizing windows for peak cooling load reduction may result in the reduction of desired heat gains in the winter, but often more than make up for it due to annual energy use reductions. Peak solar targets are often set per ft^2 of floor area in the zone adjacent to the window, though they can be translated into irradiation per ft^2 of glazing area for solar irradiation analysis mapped onto windows. Thermal storage can also help reduce peak loads.
4. *Shading only*. Some warm or hot climates need little or no solar heating. Façade design becomes a balance between light, views, orientation for pleasant breezes, and reducing unwanted solar gain year-round. In extremely hot climates such as Riyadh, Saudi Arabia, conduction through the glazing has a much larger impact on annual cooling energy with only minimal impact from shading; in these climates, it is important to first minimize the glazing percentage. Unless natural ventilation can provide almost all of the cooling, overall glazing areas should be optimized, oriented and shaded to minimize loads.
5. *Sunspaces, such as double-skin façades*, are part of another solar design strategy. This strategy uses an unconditioned space between an outer single-glazed layer and an inner double-glazed layer. The unconditioned space is meant to super-heat during some periods: the extra heat can be vented to the outside in warm conditions using the stack effect to draw in cooler air, or provide a source of heat and an extra layer of insulation during cooler periods. The unconditioned space is not usually occupied except as residential bonus rooms, enclosed balconies or sky gardens.



7.2

Solar path analysis, looking east. Unfortunately, fixed shading that reduces heat gain in the cooling month of September also reduces heat gain in the heating month of March. Solar path analysis from Ecotect using Toronto Airport weather data.

Source: Courtesy of Callison.

Double-skin façades connect sunspaces vertically to create strong air convection currents between the layers of glazing. The unconditioned space is used to trap heat in winter; in summer, the top and bottom are opened to allow convection to cool the façade. Double-skin façades were popular in Europe in the 1990s, but have lost their popularity due to mixed data on performance. Designing effective double-skin façades requires the right climate, orientation, height, and intricate use of airflow software for thermal simulation.

WHEN IS SOLAR GAIN DESIRED?

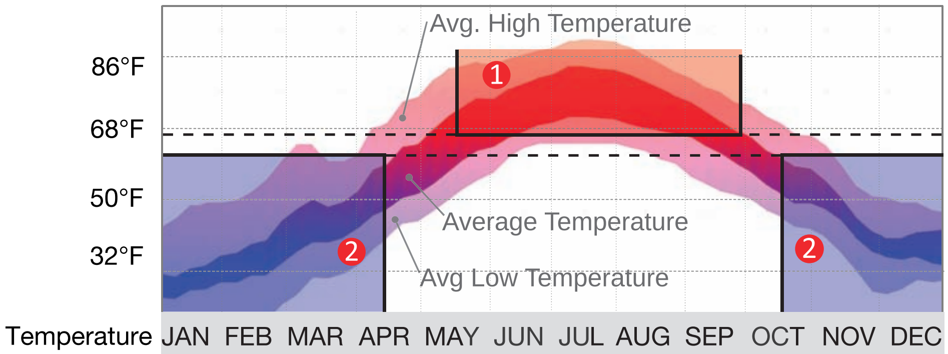
Once the solar strategy has been established, the next step is to determine the months and times of day when solar gain is desired. This data is combined with daylighting goals to help locate and orient glazing on the building. The chosen strategy becomes a baseline for testing fenestration size, orientation, glazing properties, and design of shading systems within later simulations.

For project teams with access to concept-level shoebox modeling, specific parameters can be set for shading and the maximum desired solar loads, as well as interaction with thermal mass and other project parameters, see Case Study 7.3. For other projects, several simple methods described below can be used to determine the optimal months to orient glazing towards or away from solar angles. In general, this effort should be designed according to monthly average since each year the weather will vary.

The months chosen for shading or exposure are modified by the building's internal heat load. Offices and data centers tend to have high internal loads, and require cooling most of the year. Residential properties and hotels tend to have lower internal loads and are in heating mode for a higher percentage of each year. Cooling can be done with low energy intensity during mild seasons, often directly using outdoor air, so excess solar gain can be removed more easily during this period.

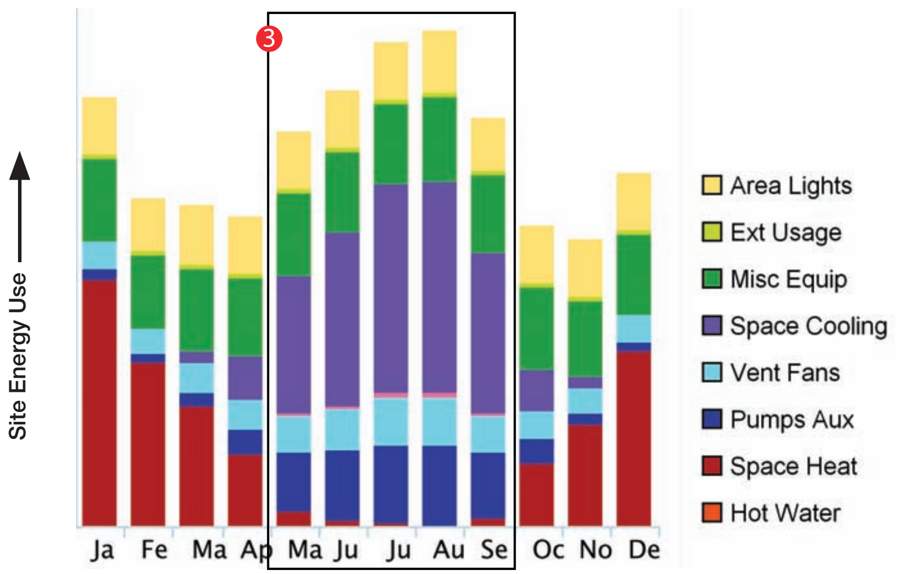
The Temperature Method

The quickest and least accurate method uses the average temperature profile as a starting point. Solar heating may be more desirable in months with average temperatures below 55°F (2), while avoiding solar gain is generally better in months above 60°F (1). Super-insulation and higher internal loads lower these numbers.



7.3 Temperature Method. Annual temperature profile, with estimated heating and cooling seasons highlighted.

Source: Ecotect outputs of annual weather data from Central Park in New York City.



7.4

Shoebox Model Method. Monthly energy use profile for an office floor plate in New York City. The simulation was performed in Green Building Studio using a shoebox model.

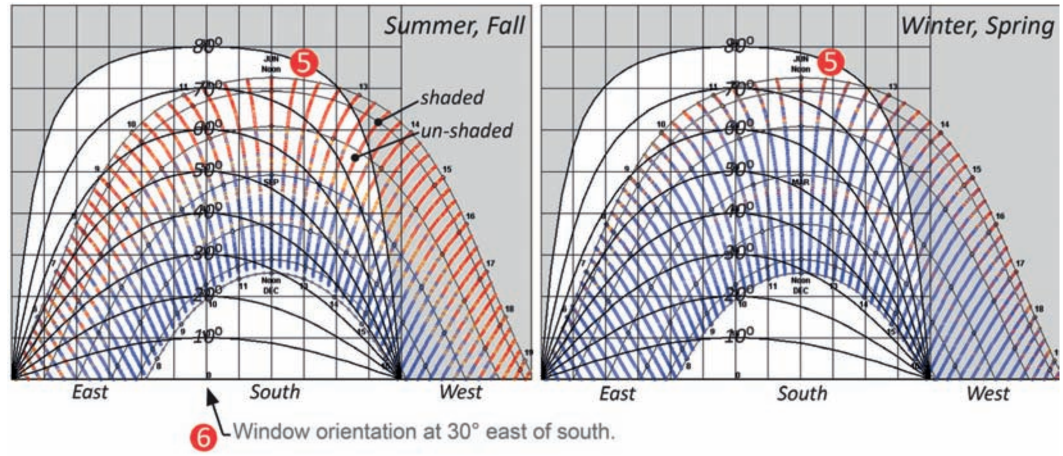
The Shoebox Model

A simple, automated shoebox model can generate a more accurate illustration of months requiring shading design. For this analysis, a thermal zone with glazing was uploaded from Autodesk Ecotect to the Green Building Studio to run an EnergyPlus simulation. Months where cooling energy is high (3) are chosen for shading. This example seems to require more cooling than the temperature method example because the shoebox model uses an office typology, where people, equipment, and lighting add heat during the day.

Climate Consultant

Climate Consultant software allows a solar path view of shading from the window's vantage. Hours of the year are plotted along solar paths, with red, yellow and blue signifying hot, comfortable, and cold outdoor temperatures, respectively. The gray area (5) represents hours blocked by a horizontal shading device. In figure 7.5, the shading device extends to an 80° angle above the window sill and provides some solar protection, especially on June afternoons. From Chapter 6, however, we know that over 50% of the solar energy is reflected by the window glass at this angle. Other shading depths can be tested by stretching the angle of the shading device. The example window is oriented at 30° east of south (6), but the orientation angle can be changed as well. Since solar angles are symmetrical about the equinoxes, both the Summer/Fall and Winter/Spring need to be considered simultaneously.

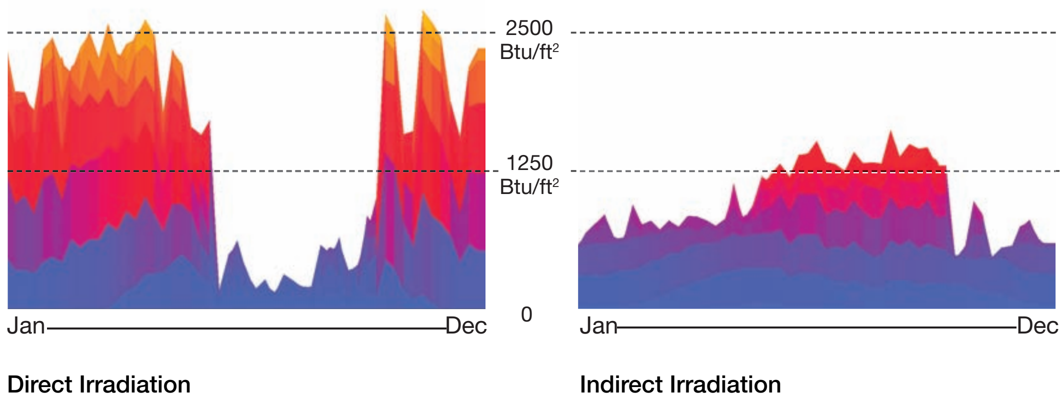
Another method asks the project engineer to set the desired irradiation levels to reduce peak loads. The architect then has the freedom to orient, size, shade, and then simulate fenestration to meet the criteria, as shown in Case Studies 7.3 and 9.1. Case Study 7.5 contains another method.



7.5

Climate Consultant software allows a quick interactive estimation of shading effectiveness at various orientations and shading depths.

Source: Courtesy of UCLA Energy Design Tools Group, http://www.energy-design-tools.aud.ucla.edu/.



7.6

Profile view of direct solar irradiation throughout the year in Mumbai, India. Direct irradiation is very high throughout the year, except during the summer monsoon when indirect irradiation peaks.

SOLAR IRRADIATION MEASUREMENT

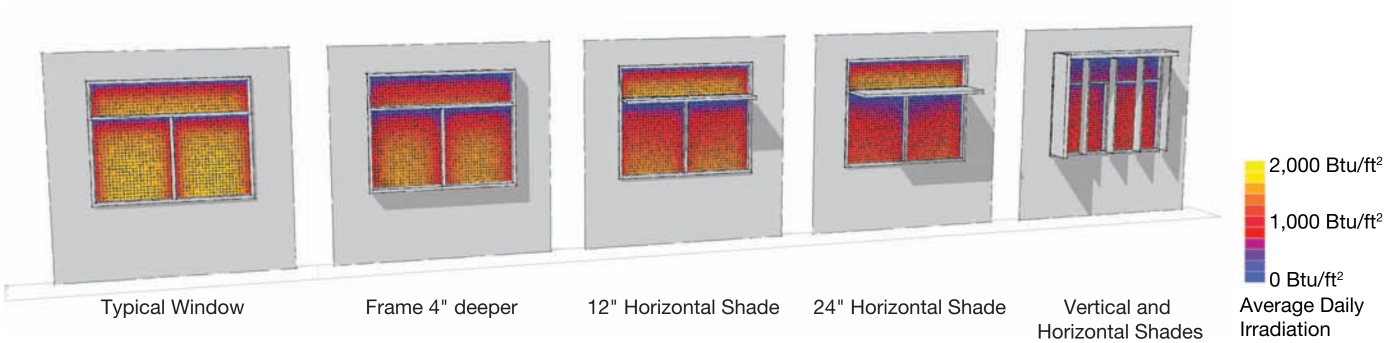
As discussed in Chapter 4 on climate analysis, solar energy falling on a surface is measured instantaneously as solar irradiance (also referred to as insolation or radiative flux). Irradiation values at the Earth's surface change throughout the day due to cloud cover and the sun's changing angle with the atmosphere. Peak irradiance values may be around 300 Btu/h/ft^2 in Melbourne or Riyadh. Comparatively, London or Seattle in the winter may have peak values of 30 Btu/h/ft^2.

The amount of solar irradiation on a surface, such as a window, over the course of an hour or day is called hourly or daily irradiation and is measured in Btu/ft^2. This calculation can include both direct irradiation, which is blocked by orientation and shading, and indirect solar. Indirect solar energy is difficult to block since it includes solar energy reflected from particles in the atmosphere and clouds, the ground, a water body, or a nearby glazed building.

Since indirect solar irradiation can be over half of solar energy received on an overcast day or when the sun is low in the sky, software that simulates solar energy needs to include reflections from surrounding surfaces.

There are currently two main approaches to calculate the amount of irradiation on each surface of the building: time-step and cumulative. The time-step method usually simulates each hour individually based on solar position and indirect irradiation from a weather file. In most software that uses this method, reflections from the ground or other buildings are either not considered or only use a diffuse irradiation multiplier to save computational time.

The cumulative method uses the same protocol as daylighting sky simulations. The software generates a single sky that accounts for solar irradiation for an entire day or month based on climate data. This method then uses raytracing for solar calculations. This has the advantage of allowing light to reflect



7.7

Shading options can be compared to determine effectiveness for a specific orientation for daily loads in Btu/ft², shown here, or peak loads in Btu/h/ft².

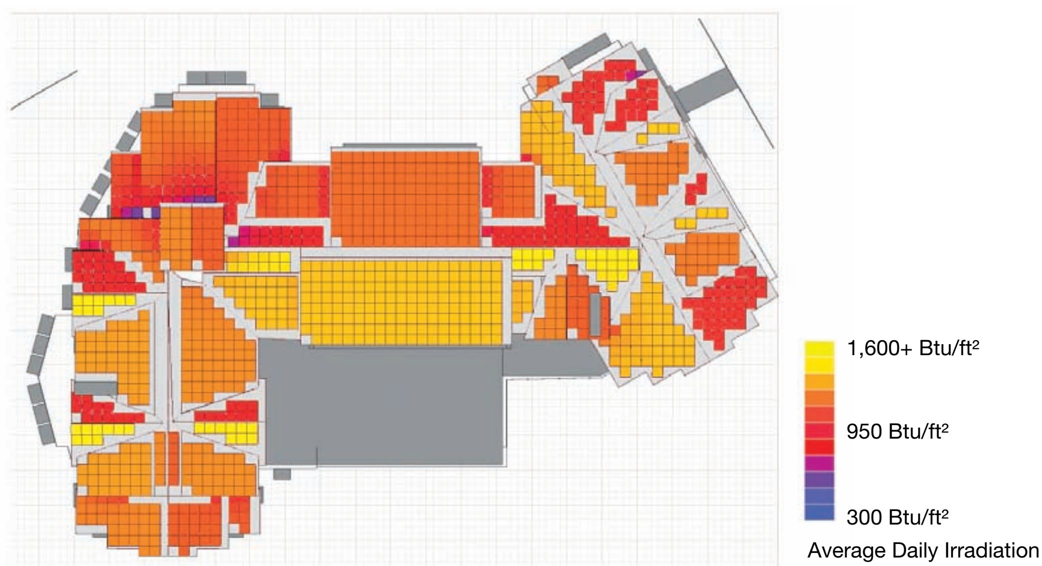
Source: Autodesk Ecotect output using Miami, Florida, weather data. Courtesy of Callison.

off the ground and other objects; however, it is generic enough so that simulations run over short time periods are less accurate than the hourly method.

Calculations for the percentage of solar irradiation that becomes a heat load inside a building can be done in conceptual design by using the calculated solar irradiation received by the outside of a window, and multiplying by the glazing SHGC and a glazing cleanliness factor of .9 for vertical and .75 for horizontal. Case Study 7.5 contains an example of this method. For more detailed heat load studies, the calculation includes glazing properties such as reflectance, the angle of solar incidence with respect to the glazing, and a more detailed understanding of frame depth and shading, described in Chapter 10.

In designing smaller buildings that will use passive solar as the primary heating source, Passivhaus PHPP software contains a proven methodology to estimate solar heat loads. Though the spreadsheet-based software (PHPP) is a complicated tool that requires training, the accuracy of the simulation has been validated in thousands of buildings in Europe that achieve an EUI of around 10–15 kBtu/ft²/year. It includes reflections due to the solar irradiation angle with glass, glazing cleanliness, and a more comprehensive concept of SHGC. See Case Study 10.4 for an example.

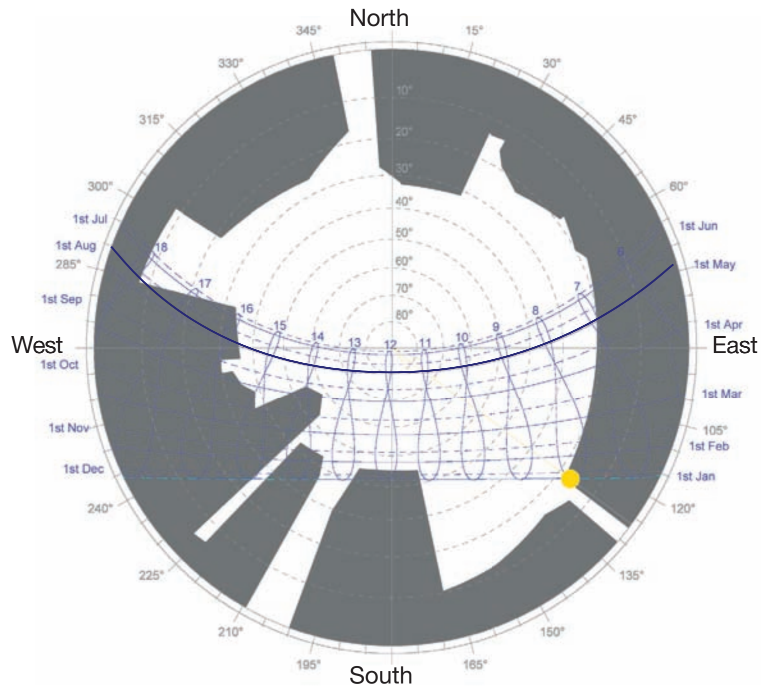
On-site renewable energy systems for solar thermal and photovoltaic can be estimated in early design using irradiation analyses as well. The manufacturer's listed panel or tube efficiencies can be used as a multiplier for irradiation results. Case Study 7.5 illustrates how panels were sized for the Net Zero Energy Bullitt Center. Each manufacturer of renewable energy uses specific criteria to estimate annual and peak power output. Photovoltaics, for example, produce less power above certain temperatures, and produce varying amounts of power from direct and indirect irradiation depending upon the manufacturing process.



7.8

Roof plan with annual solar irradiation analysis to show ideal orientations and roof forms for renewable energy collection using Autodesk Ecotect.

Source: Courtesy of Callison.



7.9

Fish-eye image showing annual solar path and adjacent buildings that shade a location within an urban context. Afternoon hours in the summer are mostly shaded, while the first two hours of each day are also shaded. The peak summer cooling date is highlighted, showing full shade after 4 p.m.

Source: Modified Autodesk Ecotect output. Courtesy of Callison.

SHADING TYPES

To receive the right amount of solar gain through fenestration, the architect needs to consider a wide variety of surfaces that may provide shading or solar reflections, including the following.

Fixed Shading

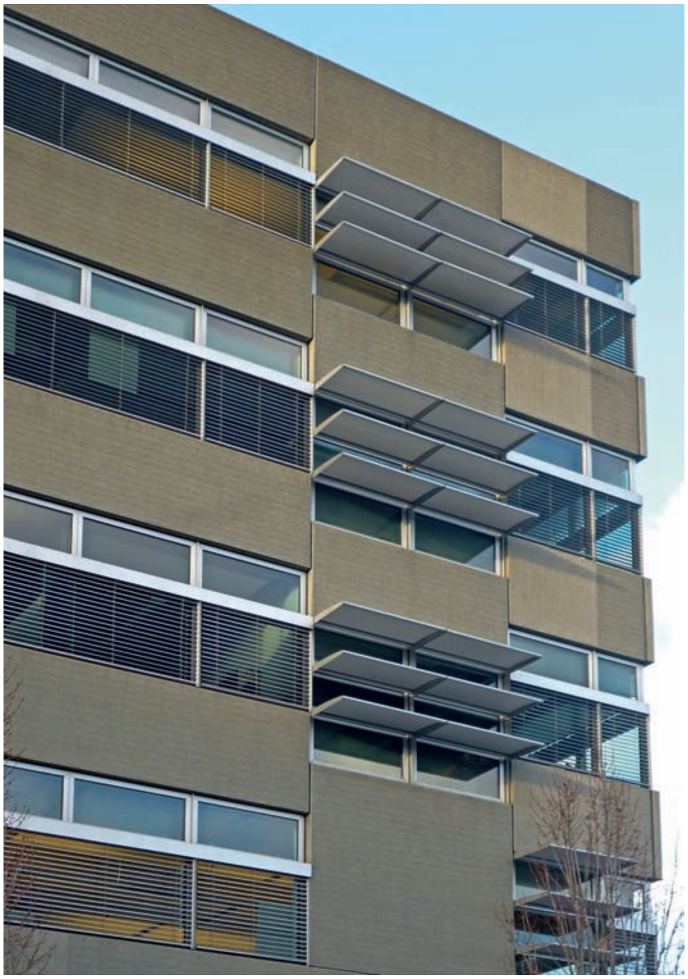
- Context, including other buildings and geography.
- Self-shading, where the building geometry provides interior corners or floor overhangs that shade glazing.
- Opaque or translucent materials, designed specifically for shading.
- Window properties, including frame depth, glass, and coatings that reflect or absorb heat.

Operable Shading

- Context, including trees and green walls that change seasonally, grow, and die.
- Awnings that can be adjusted daily or seasonally.
- Exterior or interior blinds, curtains, roller shades.
- Electrochromic glass that changes solar heat gain coefficient properties.

While contextual shading often comes from adjacent buildings, it can also include trees or terrain. Terrain shadows can be simulated using Google Earth, or simply by taking a fish-eye photo pointed straight upward and, overlaying the sun path. For Case Study 7.3 in Vail, Colorado, the adjacent mountains changed sunrise and sunset times by an hour each day, along with available solar energy.

In general, exterior shading should be as low-tech as is reasonable. A summer awning that is retracted in winter is low-tech, low-cost, and fairly effective. Systems for high-rise buildings, especially operable shades, need to be wind-resistant, require minimal maintenance, and be integrated into the building controls. For these reasons, high-tech shading is required.



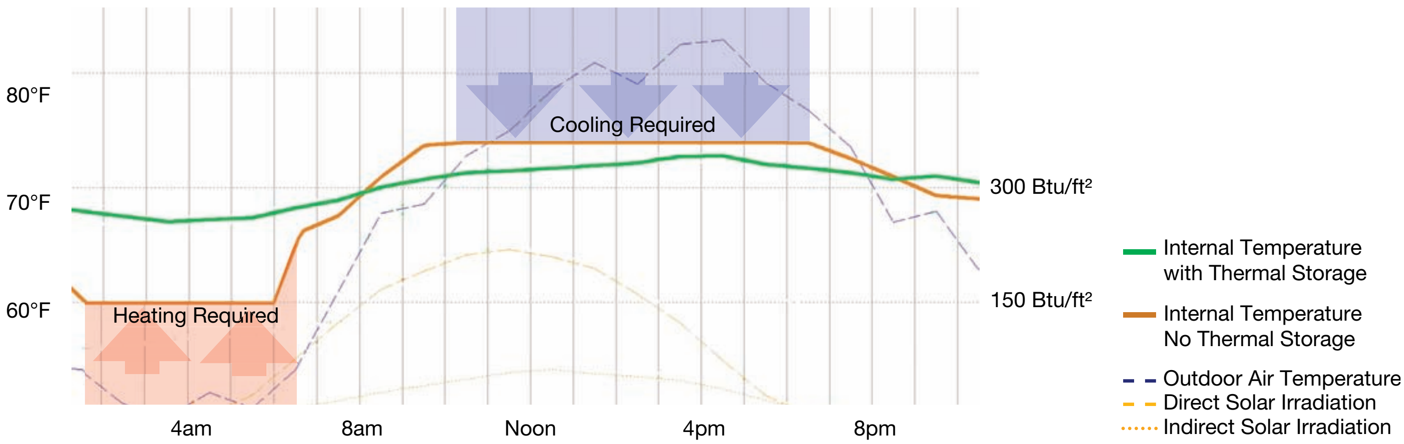
7.10

External fixed and operable shades can be integrated into the façade design, blocking glare or heat gain for the lower "vision" glass, leaving the upper "daylight" glass able to provide daylight deep into a space.

Operable shades are, in theory, much more effective than fixed shading. They can respond to atypical seasonal weather conditions, and they can respond to hourly and even minute-by-minute weather variations. With detailed energy modeling, operable devices can be shown to provide significant additional comfort and reduced energy use. They may allow the owner to save the capital cost of an air conditioning system altogether, like the Terry Thomas building in Seattle, designed by Weber Thompson (Figure 7.10).

Operable, exterior shading has drawbacks that have limited their use, though. In most cases physical actuators are necessary, and operable parts are subject to expansion and contraction from solar energy, daily and yearly temperature cycles, freezing, precipitation, wind, and vandalism. They need to be programmed and operated properly, be correctly tied into a central building management system (BMS), and earn occupants' complicity and understanding.

Exterior blinds and roller shades are generally mounted on tracks or guide wires along each side. Exterior roller shades preserve views like interior shades, but block nearly all solar energy when deployed. They are automatically retracted at wind speeds above 15–25 mph and may fade since the fabric is exposed to ultraviolet rays and weather. Exterior metal blinds can withstand higher wind speeds and have longer lifespans but limit the view when deployed. Operable devices within IGUs or double-skin façades are much more protected, but trap heat within the IGU instead of outside it.



7.11

Diagram showing air temperatures over a 24-hour period for an office with and without thermal storage.

Source: Modified output from an Autodesk Ecotect building model. Courtesy of Callison.

THERMAL STORAGE

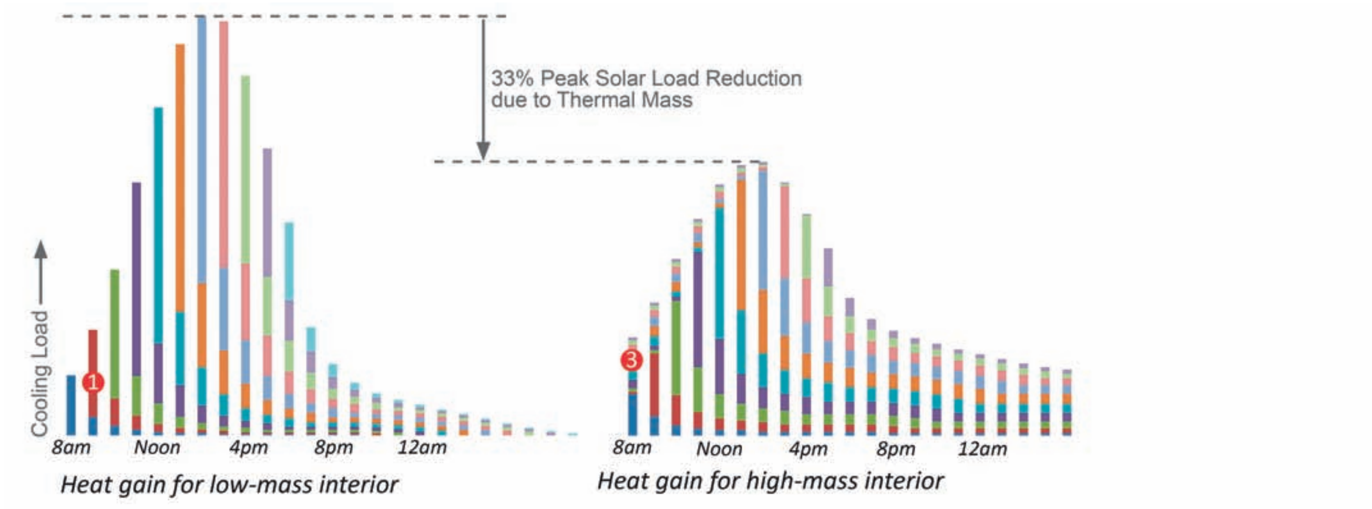
Although thermal storage can be an important part of maintaining comfort with minimal energy inputs, over the past 200 years construction in much of the First World has tended towards lightweight, insulated buildings. Lightweight buildings are typically less able to use solar energy, since they cannot delay or store the few hours of intense solar heating each day. Thermal storage acts as a battery that spreads solar loads over a 24-hour cycle, reducing peak heating and cooling loads and associated costs. Thermal storage is effective in nearly every climate except year-round hot-humid climates; it is especially effective in arid climates.

Figure 7.11 shows simulated inside air temperatures over a 24-hour period in a single south-facing zone of an office building in Denver, Colorado. The green line shows the inside air temperature with 8″ CMU thermal mass; the brown line shows the temperature in the same building with lightweight construction. Temperature in the option with thermal mass stays within the comfort zone throughout the day, and does not require any mechanical heating or cooling.

The option with no thermal storage requires both heating and cooling within a single day. A mechanical system keeps the office zone at a night-time low set-point of 60°F. At 6 a.m. the set point goes up to 68°F to preheat the building for the occupants. By the time the sun's heat begins hitting the east façade around 7 a.m., the office is filling up with people, who turn on computers, copier machines, and lighting, which all add heat to the space. The sun adds significant heat gain as well and the maximum set point of 73°F is quickly reached in this zone. The mechanical system switches to cooling mode around 9:30 a.m., just 3 hours after pre-heating the building. Cooling is necessary until 6:30 p.m., when the occupants leave and outdoor temperatures allow the building to cool naturally. The heating system turns on around 1:30 a.m. to maintain the night-time set-point temperature.

Thermal storage is reheated each day by exposure to the sun and internal building loads. It is cooled at night through natural ventilation, heat loss through the envelope, or night-time mechanical cooling. For naturally ventilated buildings, thermal storage should be along the main path of cooling breezes, so excess heat can be stored and removed through daytime or night-time ventilation. For stack effect-driven natural ventilation, thermal storage at the end of the natural ventilation path will absorb more heat during the day, and will be cooled less by breezes at night.

Thermal storage that absorbs energy during the day can reduce peak loads and overall energy intensity—even if the storage is mechanically cooled at night. Night-time air temperatures are lower, allowing a night-time mechanical cooling system to remove daytime heat while using less electricity.



Percentage of Solar Gain released during each hour after being transmitted through glazing

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
High Thermal Mass Example	27%	13%	7%	5%	4%	4%	3%	3%	3%	3%	3%	3%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	1%	1%
(2) Low Thermal Mass Example	55%	17%	9%	5%	3%	2%	2%	1%	1%	1%	1%	1%	1%	1%	-	-	-	-	-	-	-	-	-	-	-

7.12

Solar irradiation values on a south-facing window in Toronto with a .50 glazing to wall ratio were imported onto a spreadsheet to calculate thermal mass effects on peak solar loading using the Radiant Time Series (RTS) method. Each hour's transmitted solar energy becomes a cooling load to the zone over the next 24 hours according to the percentages below for a low-mass and high-mass interior, which are color-coded to show the cumulative effects. At 9am, the solar irradiation that enters is colored red (1), and can be tracked over the next several hours until it becomes nearly negligible. For the low-mass option (2), 55% of the solar energy becomes a cooling load within the same hour it reaches the zone, and 27% is delayed until the second hour, with 9% becoming a cooling load in the third, etc. Each hour has been assigned a color to track it through the day, with the high-mass system including a small remaining solar load from the previous day (3) over the first several hours. The Radiant Time Series method (ASHRAE, 2013) is used to estimating peak cooling loads and contains an accurate but simplified version of estimating the time-delay of solar gain in low-, medium-, and high-mass constructions. The low-mass construction contains carpet, while the high-mass construction exposes concrete floors. The time-delay of other elements, such as exterior walls and solar energy absorbed by the glazing, was not considered. Solar irradiation values calculated in Autodesk Ecotect.

Source: Courtesy of Callison.

Since peak loads drive equipment and duct sizes, thermal storage also reduces first cost. Controlling peak energy use also allows radiant systems to be used, which are generally more efficient at providing comfort. In addition, peak cooling determines the temperature of air that the chiller provides throughout a building, thus lowering the spaces with the greatest peak loads can result in a higher overall supply temperature, further reducing energy use.

Thermal storage is generally most effective when adjacent to windows as it affects spaces in two ways: it absorbs or releases sensible heat to a space, affecting the air temperature, and can also counteract radiant energy from nearby areas of glazing. For example, window glass radiates cold temperatures in the winter that may decrease thermal comfort, even where the air temperature is otherwise pleasant. Nearby thermal storage will radiate its warmer temperature, thus reducing an individual's net radiant heat loss in the direction of the window.

Types of Thermal Storage

All materials absorb radiant energy and then release it by conduction, convection and radiation over many hours. Thermal storage refers to materials and assemblies that are able to absorb more energy and release it more slowly. Thermal storage systems can be created with exposed thermal mass or phase change materials.

7.13

Phase change materials (PCMs) may be purchased in sheets with small packets of PCM material. This installation photo shows PCM being laid on top of ceiling tiles at the University of Washington Molecular Engineering and Sciences Facility. Sheets may also be attached to studs just before finish materials are attached.

Source: Courtesy of ZGF Architects.

Though concrete-framed buildings contain plenty of thermal mass, contemporary designs generally deaden thermal storage effects by covering the concrete with carpet, wood, furring, and other insulators. Only hard, massy finish materials directly applied to the thermal mass, such as gypsum board or non-porous stone, will enable the effects.

Water is the most common thermal storage phase change material (PCM) historically. The first air conditioners were built to freeze water at night, with daytime cooling provided by blowing air over the ice, which is where the term "tons" of cooling comes from. In modern ice storage systems, thermal loops exchange heat with the ice the following day to provide cooling and reduce peak loads.

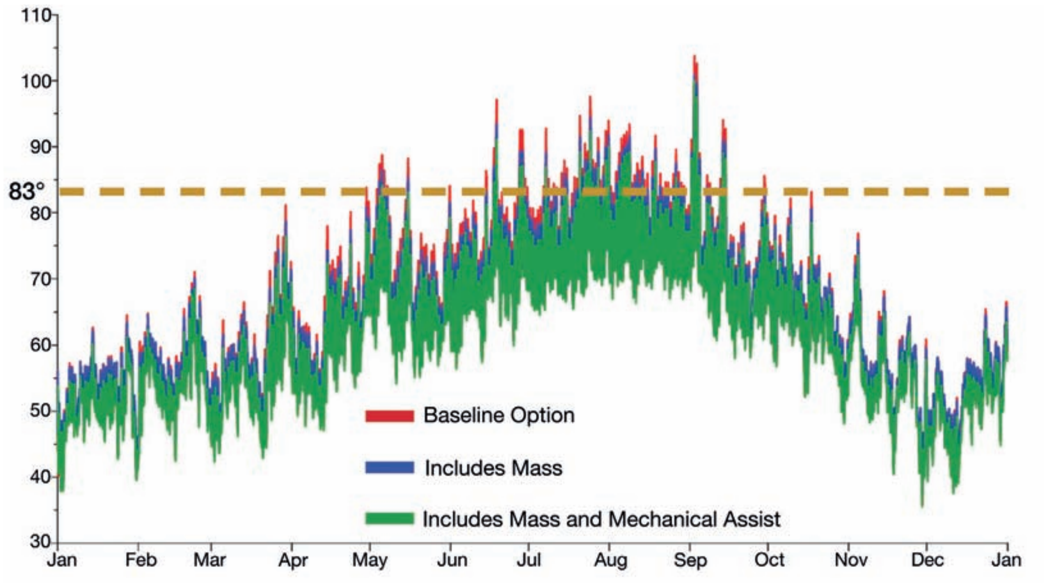
Lightweight buildings can use modern PCMs that mimic some effects of thermal mass. They weigh much less than traditional thermal mass and are thus suitable in retrofit and high-rise applications. In this book PCMs are considered interchangeable with thermal storage, except as noted here.

Lightweight PCMs change state at a designed temperature such as 74°F, so they can absorb large amounts of energy when a room's temperature exceeds this amount. They can then release the energy when the temperature drops below their freezing point. However, a space that remains above the PCM's freezing point during the night cannot absorb any energy the following day. In this case, thermal mass would be superior as it would still have cooled off somewhat during the night. Most software engines include or will soon include assemblies that model PCMs.

Super-insulation and air-sealing allow all elements within a building to maintain a fairly consistent temperature day to night, effectively storing energy even in low-mass buildings.

Thermal Storage Measurement

Thermal mass stores sensible energy. The amount of thermal storage available in a material is measured as a heat capacity, with units in Btu/°F, and is a combination of the material's specific density and the specific heat capacity. Emissivity and conductivity of the material are also important as they determine how easily a material will receive and transmit stored energy. Thermal mass interacts with spaces in direct proportion to the temperature differential, meaning that thermal storage is most effective at moderating temperatures during peak heating and cooling times.



7.14

An energy model predicts hourly indoor temperatures based on three options. The third option lowers the indoor temperatures so that >97% of occupied hours (8 a.m.–8 p.m.) are below 83°F, allowing natural ventilation to provide a level of cooling acceptable to the client. See Case Study 9.1.

Source: Courtesy of ZGF Architects.

In reference books, thermal mass is often measured by volume, such as a 4″ deep concrete slab, 20′x30′ in plan view. Simulation software generally categorizes thermal mass within assemblies as low-, medium-, and high-mass. If more detail is necessary, complicated algorithms are required that calculate the absorption and release of energy from each surface.

Instead of storing sensible energy like thermal mass, PCMs store latent heat from freezing and thawing. When a space's temperature rises above a PCM's freezing point, the PCM melts, absorbing heat. The heat is released when the space's temperature drops below the freezing point. One manufacturer offers PCMs with freezing points at 23°C, 25°C, 27°C, and 29°C.

M-value, a metric created by the PCM industry, refers to energy stored per square foot of material. The M-value of a material ranges up to 100 Btu/ft^2 or more. The industry claims that 1/2″ of PCM stores thermal energy as well as 12″ of concrete. The research community is still testing to see the applied results of PCMs over time and in various field conditions.

Thermal storage is sized for optimal performance through iterative simulations using energy modeling software, covered in Chapter 10. However, some energy modeling software does not account for thermal storage effects, so research must be done to discover if and how the thermal engine considers mass and PCM materials.

Diagrams 5.7–5.9 show an earth-tube system of storing thermal energy, and Chapter 10 covers how thermal mass enhances the U-value of a wall assembly.

CONCLUSION

Solar irradiation is free energy that can be harvested for use in buildings. While it is a local, intense heat source that can cause discomfort, a good design captures and stores the right amount of heat, blocking the rest. Setting a solar strategy, determining the months where solar gain should be allowed or excluded, helps a project team with building and glazing orientation, and later helps the team design appropriate shading devices. Thermal storage allows the intensity of the heat source to be spread out over a day or more. While this process can be done intuitively, validating a design with simulation is key to ensuring that chosen strategies will be effective.

7.1 PEAK SHADING DESIGN

Project type:
18-story office building (existing, 1974)

Location:
Portland, Oregon

Design/modeling firm:
SERA Architects and Cutler-Anderson Architects with Stantec Engineering

Peak loads determine mechanical equipment sizing, as well as mechanical system selection. Choosing the right glazing percentage, orientation, and shading for all façades can be informed by peak loads targets. The process of designing shading needs to balance heat gain, daylighting, and glare.

Overview

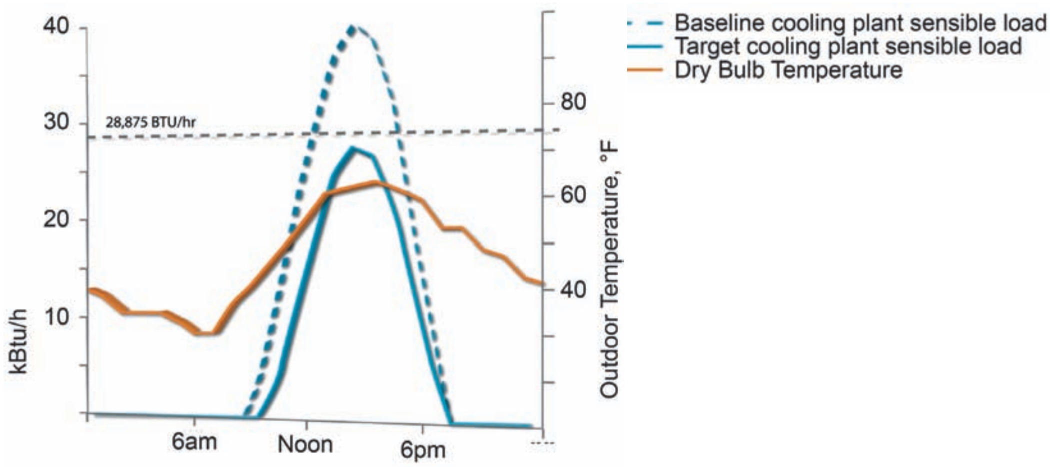
The Edith Green–Wendell Wyatt (EGWW) Federal Building, an 18-story, 512,000 sq ft office tower located in downtown Portland, needed a major renovation by 1996, when the General Services Administration (GSA) commissioned a comprehensive study to analyze the architectural and engineering system deficiencies. In 2003, SERA was hired, along with Cutler-Anderson Architects, for the design of repair and alterations as part of the design excellence program.

In 2009, the project was brought back to life by the American Recovery and Reinvestment Act (ARRA). A cost benefit analysis revealed market changes in both the cost of construction and nearby lease space, which made it more economical to completely vacate the building during a renovation. This was a game changer for the project, creating the opportunity to achieve deep energy savings.

7.15

View looking southeast.

Source: © Jeremy Bitterman



7.16

Peak loads for a southwest facing zone occur for this building on March 15th due to the solar angles. The graph shows the reduction in peak loads necessary to provide all mechanical cooling using radiant panels.

ARRA funding required that the project meet the significant energy and water conservation requirements of the Energy Independence and Security Act (EISA). The resulting project certified LEED Platinum and is predicted to use 60–65% less energy than a typical office building. The project exceeds EISA requirements and is projected to be one of the lowest energy use office buildings in the United States.

Every building system was to be improved in the redesign effort, including a new energy-efficient building envelope; new highly energy-efficient mechanical, electrical, and voice/data telecommunications systems; a blast-resistant curtain wall; tenant and core upgrades; and seismic structural upgrades. Now that it is complete, the EGWW Federal Building is the GSA's national model for energy-efficient renovation.

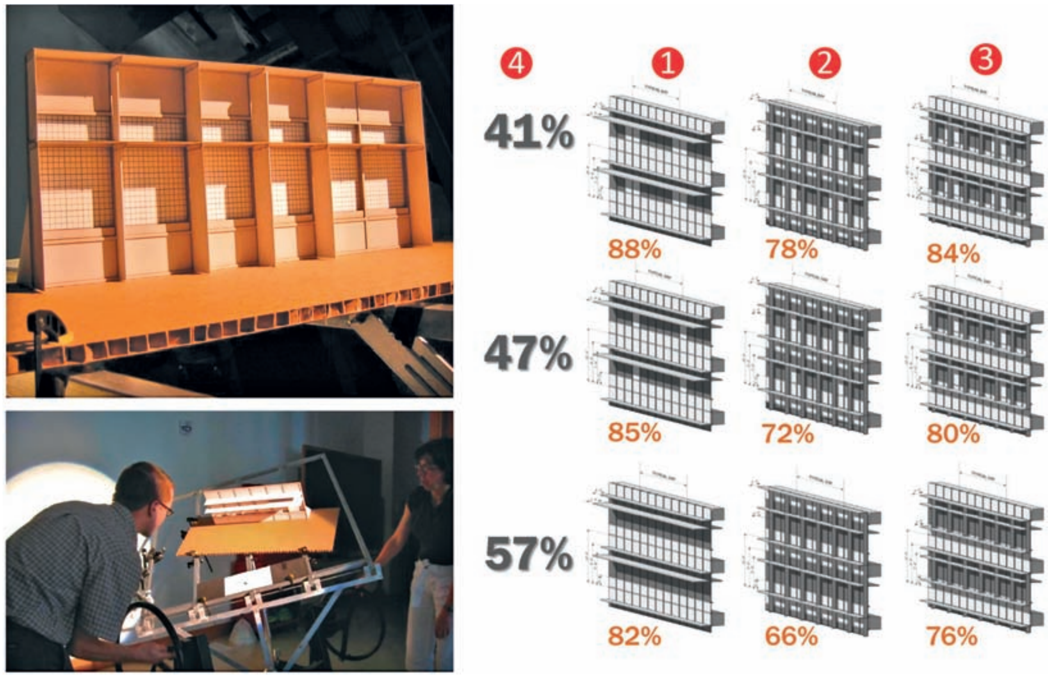
Simulation

To ensure the goals of EISA would be met, the project team performed extensive technical research and early modeling on strategies ranging from exterior shading and daylight, to thermal comfort, to occupant behavior. Incorporating radiant heating and cooling was found to be one of the top performing strategies in terms of energy savings through an energy model by Stantec Engineers.

Although radiant systems are very efficient, they cannot be expected to maintain comfort if they handle peak cooling loads over 20–30 Btu/h/ft^2 of floor area. While eQuest was used to estimate annual energy loads, Stantec Engineering used IES Virtual Environment V5.9 software to estimate peak loads for each façade. The IES model determined the amount of solar control needed to reduce cooling loads to the point where radiant cooling would be able to ensure comfort. Once the energy model was set up in IES, the "Suncast" module was used for solar calculations and the "Apache" module was used for the thermal analysis.

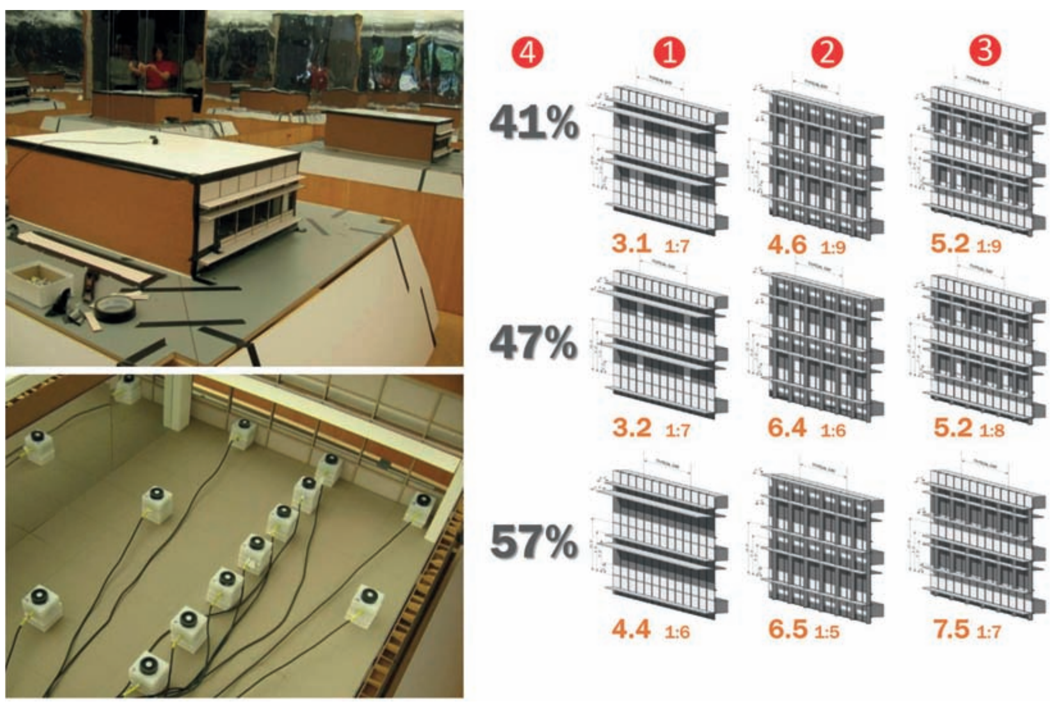
Since some of the peak cooling load would be handled by a dedicated outside air system providing the code minimum ventilation at 55°F, the total peak cooling load criteria for the space was set at 35 Btu/h/ft^2 of floor area, based on the energy model. The results of the study showed the design team which solar altitudes required shading and which did not. Each façade was tested with a unique peak condition; the example shows a southwest-facing zone, where peak loads occur on March 15th due to the low sun angles.

The next step was to determine a percentage of time that the west, south, and east façades would need to be in shade during peak cooling hours. The depth of the fixed, horizontal shading device was used as a variable, testing 6″ increments from 18″ up to 36″. The results showed that 24″ was the minimum depth that provided the shading required by the radiant cooling system.



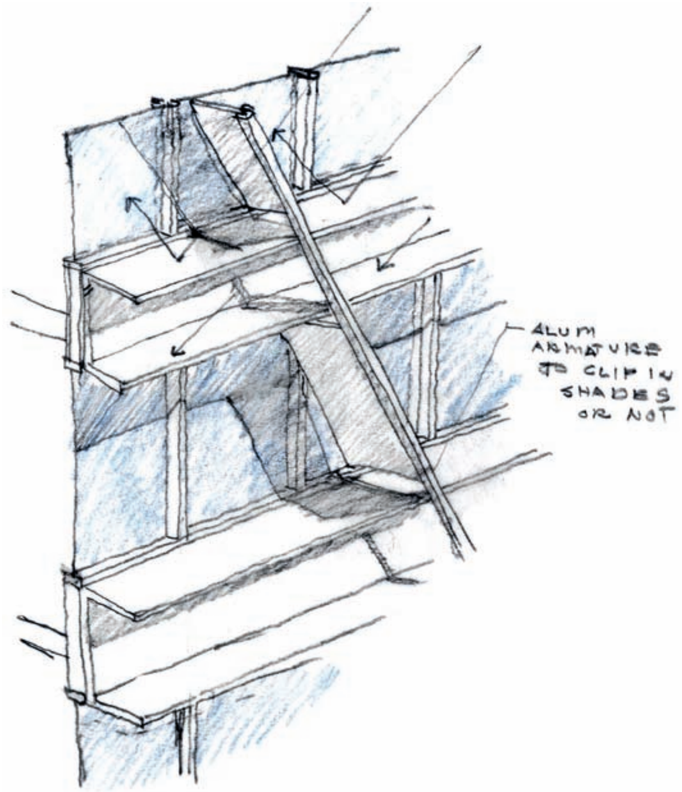
7.17

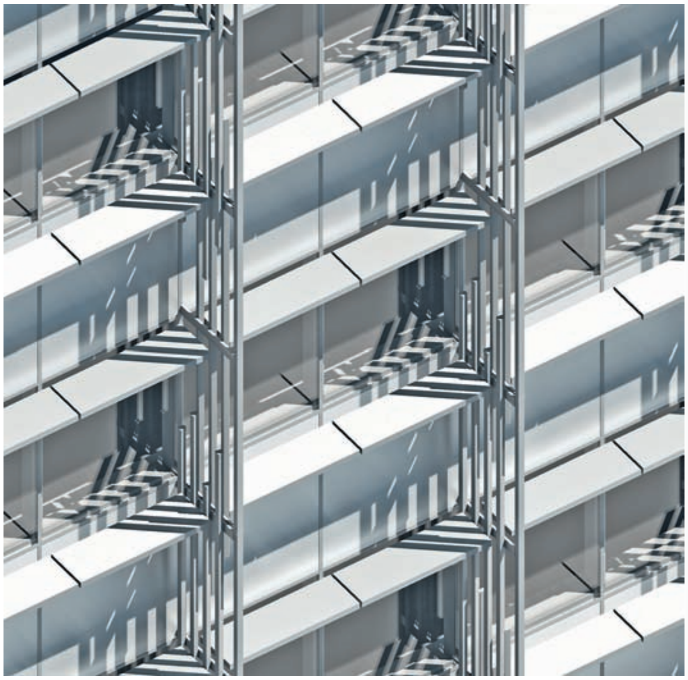
Façade shading studies testing options with (1) horizontal shade only, (2) vertical and horizontal fins with the horizontal element as a light shelf, and (3) vertical and horizontal fins with the horizontal as sill reflector. Each option was tested with 3 glazing percentage options (4). The orange number shows the percentage of the glazing that is shaded in each option.



7.18

Daylighting studies testing the same 9 shading options as 7.17. The large orange number shows the average daylight factor in the 16′ perimeter zone, and the small number shows the contrast ratio across this area.





7.19 and 7.20

Sketch and rendering of proposed shading strategies.

Source: Courtesy of Jim Cutler.

Adding shading reduces the amount of daylight available which could drive up lighting energy use, increasing the peak load. Since many variables needed to be tested simultaneously—glazing percentage, daylighting, and peak shading—an iterative process was used.

The three different shading strategies were modeled for daylighting and shading at the University of Oregon Energy Studies in Buildings Laboratory:

- a horizontal-only condition;
- a system with vertical and horizontal fins with the horizontal element as a light shelf;
- a system with vertical and horizontal shades with a horizontal element as a sill reflector.

Each shading strategy was modeled with 41%, 47%, and 57% glazing percentages on the southeast and southwest façades. The northwest façade required a different shading strategy due to the low-angle sun and was modeled in a separate, iterative process. These studies helped convince the team that they could reach the peak load targets with 41% glazing and reasonable shading depth.

After establishing the basic parameters for the exterior shading, SERA Architects, worked in tandem with the project's designer, Cutler Anderson Architects, exchanging sketches and analytics back and forth until the daylighting and shading goals of the project were realized in form.

One of the first options proposed was a diagonal version of the shading strategy initially shown in the physical modeling. Although this option was found to meet the shading criteria, it was re-thought for budget reasons. Working back and forth through design development with input from the curtain wall manufacturer as well, a cost-effective version of the design emerged where the vertical elements of the proposed shade were vertical tubes, achieving the shading criteria by their placement relative to each other. This revised design was tested using computer and hand calculation methods to ensure the shading criteria were met.

Additional Studies

Additional variations to the shades were tested throughout the design process using a variety of different software programs, including Revit, Ecotect, Radiance, and eQuest. Hand calculations were ultimately used to validate the results of the computer and physical modeling.

7.2 SELF-SHADING

Modulating buildings, and especially residential buildings with balconies, can self-shade. Once the heating and cooling seasons are determined, simulations can be run to determine where the design provides enough shade using balconies and modulations, and where additional shading measures are required.

Project type:
42-story residential tower

Location:
Kochi, India

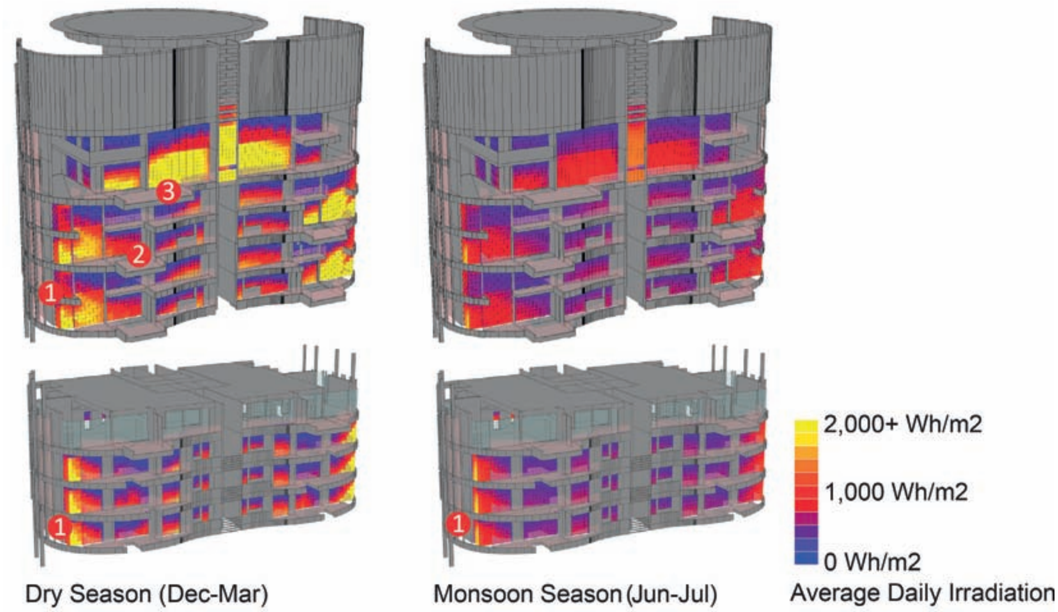
Design/modeling firm:
Callison

Overview

Kochi's climate includes year-round comfortable temperatures with daily peak relative humidity near 70%. Summers are overcast during monsoon rains with even higher humidity. Design in this climate focuses on shading, operable windows for natural ventilation, and mechanical air conditioning as a back-up system when necessary. This means a more glazed area is possible within a low-energy building when windows are properly designed for cross-ventilation. In this tropical climate, shading is designed for sunny winters with low sun angles.

7.21

Rendering of East Tower, Kochi.



7.22

Solar Irradiation studies on a southern façade during the dry season and the monsoon season.

This project includes two residential towers and a number of villas. The towers each contain 2-story units at the upper floors over 1-story units. Residential balconies and the majority of the large glazed areas were oriented to the south to incorporate views and control solar gain. Metal mesh screens provide solar control for the limited openings on the east and west façades while allowing free airflow for cooling breezes. The north side has a balcony and operable glazing for cross-ventilation.

Simulation

A detailed SketchUp model was imported into Ecotect to test the effectiveness of the shading strategies. The model was simplified to include only four floors for single-story units and six floors for 2-story units and penthouse unit. The glazed areas were subdivided into 200 mm grids to determine areas that were optimally shaded. Simulations were run from sunrise to sundown for the dry season (Dec.–March) and the summer monsoon season (June–July).

The analysis proved the effectiveness of the balcony size and location on the single-story units and 2-story units near the center of the building. The corner condition (1) required additional treatment at all units. Closely-spaced terracotta louvers were added to this area based on the simulation results. The client was very pleased with this solution as it reduces solar heat gain without compromising views of the surrounding area. At the two-story units (2), upper floor balconies shaded much of the south façade.

The Penthouse Level (3) contains operable sliders in front of a double-height living room that was shown to be inadequately shaded. Since operable sliders cannot have fixed shades or screens in front of them, the design team recommended operable blinds between the glass panes of the sliding units.

7.3 SOLAR IRRADIATION TARGETS

Shading can be designed to both maximize solar heating during winter and minimize solar heating during summer. This requires a method to determine months when shading is desired and when solar gain is desired.

Project type:
Residential and hotel over retail

Location:
Vail, Colorado

Design/modeling firm:
Callison

Overview

As currently proposed, the Ever Vail project is a large, mixed-use development masterplan that includes dense development with condominiums over retail, a new enclosed transit center, office space, a hotel, a children's recreational center, and other amenities. Ever Vail has achieved LEED for Neighborhood Development Platinum (Stage 2).

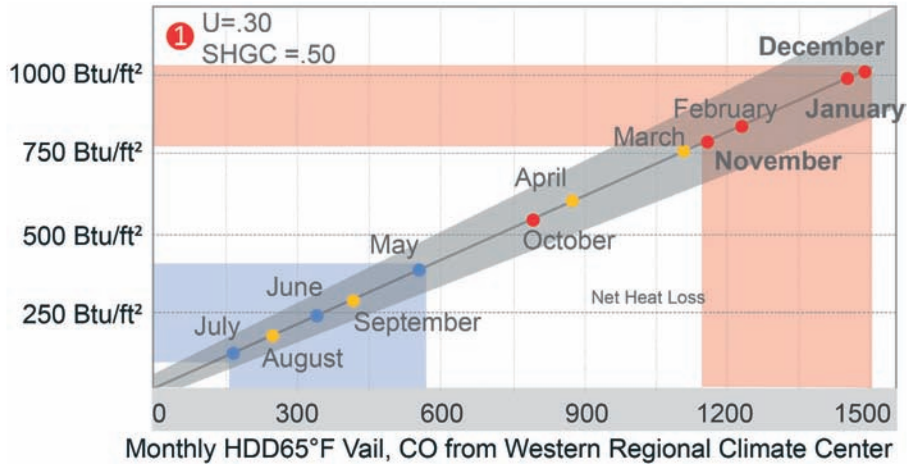
The project began with initial studies of possible site configurations, including optimizing views and solar orientations. Double-loaded corridors that allow dense development and minimize envelope area and heat losses preclude each residence from being entirely passively heated—either the south-facing units would receive plenty of heat with easy control, or else east- and west-facing units receive half a day's sun with more difficult solar control. Due to site planning issues, some of each were incorporated.

Early in the design process, as described in Case Study 5.4, the potential for overheating was brought up. In this extremely cold but sunny climate, overheating frequently happens near large glazed areas. At night the heating system maintains a comfortable temperature, but when the day begins with intense sun, cooling quickly becomes necessary. Thermal storage strategies were shown to be extremely

7.23

View of Gondola Plaza at Ever Vail.

Note: Photos, rendering, and data related to the Ever Vail development are courtesy of Vail Resorts Development Company and may not be reproduced without permission.



7.24

Approximate desired average daily solar irradiation at the outside of glazing, assuming some thermal mass.

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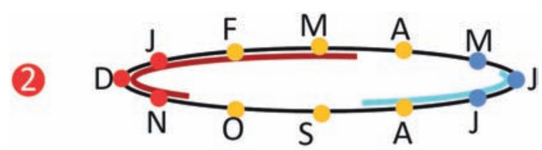


7.25

Months of the year shown red for heating-dominated and blue for cooling-dominated, based on a simple energy model.

Note: Photos, rendering, and data related to the Ever Vail development are courtesy of Vail Resorts Development Company and may not be reproduced without permission.

effective in reducing heating and cooling within the same day, and storing each day's solar gains to be used at night.

Two solar strategies were considered. The more traditional approach used a low SHGC to limit solar gain year-round, reducing cooling in summer, but also desirable heat gain in winter. A more effective option used a higher SHGC (>.50) along with external operable shades, allowing desirable heat gain and blocking undesirable heat gain.

This case study looked at the second solar strategy to determine if external, operable shades could be minimized due to their maintenance requirements and cost. Since a complicated geometry with roof overhangs was necessary to meet the zoning code, these design moves could also provide shading in some areas, reducing the quantity of external, operable shades.

Simulation

In order to begin this analysis, the design team needed a rough idea of how much solar gain was desirable on each façade and the time period where self-shading was desirable.

A graph showing heating degree days for each month on one axis, and desired solar irradiation on the outside face of the window on the other, was created based on balancing daily solar heat gain with conductive heat loss through the window. A wide line showing the balance, based on window properties, was graphed against each month's heating requirements. This approach is useful but simplistic, since it does not consider internal gains, wall conduction, or fresh air. However, it gave the team a rough target for each month of the year.

Since fixed shading blocks sun symmetrically about the solstices, a method to determine the correct months to provide shade was necessary. A simple Green Building Studio energy model was run to determine months where heating was dominant and where cooling was dominant, based on standard

7.26

Solar roses.

Note: Photos, rendering, and data related to the Ever Vail development are courtesy of Vail Resorts Development Company and may not be reproduced without permission.

occupancy with a glazing percentage at 40%. The results were simplified, presented in blue for cooling, and red for heating. Months where heating and cooling needs were minimal or overlapped were colored yellow instead.

For the solar irradiation analysis, a SketchUp model that had already been created for design purposes was redrawn to simplify the geometry, removing window mullions and other details. The 3D model was then imported into Ecotect for analysis. Each façade surface was divided into grid sensors to measure solar irradiation. Each season was run to compare solar levels to the desired solar levels.

Perspectives and elevations of the false color model were exported for the team to consider. Since windows were removed to simplify the model in the previous stage, the elevations were overlaid in Adobe Photoshop with more detailed elevations. This had the added benefit of being able to relocate windows within a façade in Photoshop to immediately determine any improvements without re-doing the solar analysis.

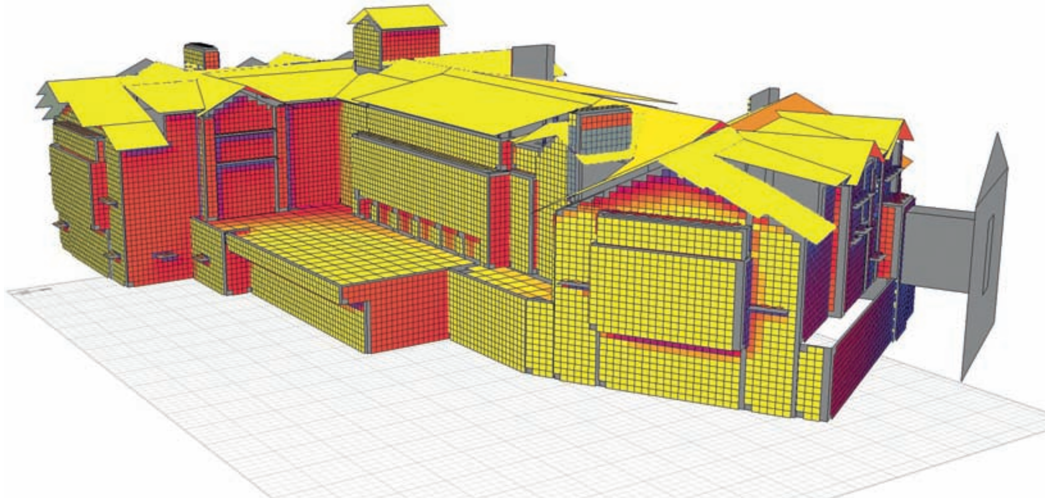
Interpretation

Vail, Colorado, receives more sun than is necessary to provide heating to a south-facing space (3) (4) on an average winter day, and about enough to ensure that windows on the east and west are net heat sources as well. This study illustrated the necessity of limiting solar gain throughout the year, even in the winter, and incorporating thermal mass to spread the intense daily heat gain through the night.

This analysis shows that the main south façade (5) is shaded during the summer at the upper floors, due to the deep roof overhang, and at the lower floors, due to recessing the windows 18″ into the façade. The shading keeps the daily solar gain below 1000 Btu/ft^2, around half of which is diffuse radiation and difficult to block.

During winter, the entire south façade (6) is exposed to more heat than may be necessary; the shading that was effective on the upper and lower floors in the summer is not effective in winter due to the low sun angle. In most cases, operable interior blinds or shades will be deployed to block the low angle sun, reducing some of the direct heat gain. The worst performing areas on the south façade (7) were recommended for operable exterior blinds.

For the west façade, nearly all windows receive enough heat to meet the threshold for this analysis in the winter. In the summer, however, some of the windows receive so much that indoor comfort conditions may be nearly impossible to maintain. In these locations (8), operable exterior blinds were recommended.



7.27

View from southeast, winter solar irradiation study.

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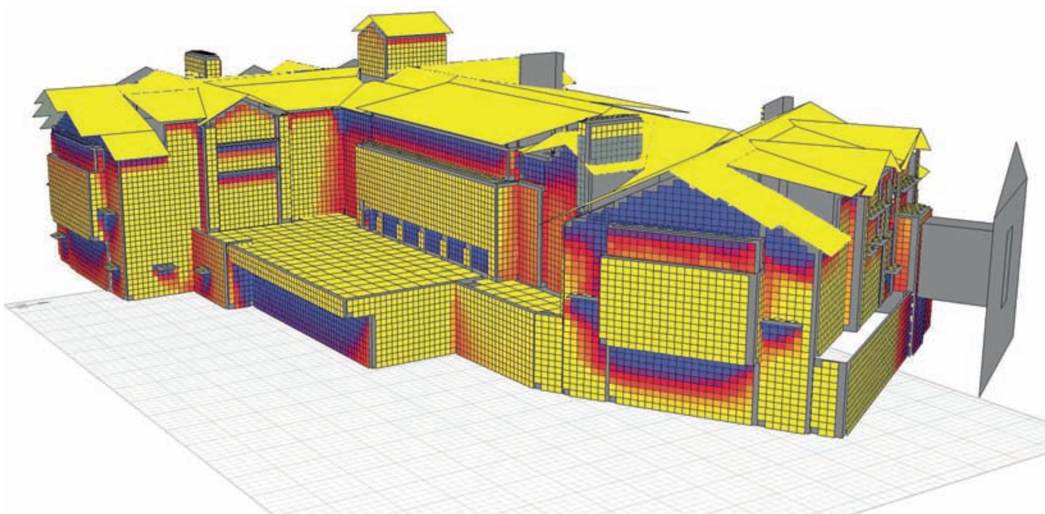

7.28

View from southeast, summer solar irradiation study.

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7.29

South elevation, North elevations, and West elevations in the summer (top) and winter (bottom).

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7.4 FIXED SHADING OPTIMIZATION

Shading optimization often depends on choosing a constant, fixed shading depth based on heating and cooling seasons. This shading depth optimization method uses energy modeling to balance desired heat gain with desired shading. The result gives a three-dimensional idea of beneficial shading, leaving the actual shading device design up to the designer.

Project type:
Theoretical study on a mixed-use tower

Location:
Chicago, Illinois

Modeling firm:
Jeff Niemasz and Jon Sargent

Overview

For their Master's thesis in architecture at Harvard University, Jon Sargent and Jeff Niemasz explored simulation methods linking form generation to data-driven design objectives. As a test case, they considered the conceptual ambitions of Aqua, a highly acclaimed mixed use skyscraper in Chicago designed by Studio Gang Architects. According to its designers, the tower's distinctive floor slabs were shaped in an effort to provide solar shading while maximizing desirable views in response to the dense urban context.

The broader goal of the thesis research was to rethink the methods that designers conventionally use for climate-based design. Taking the Aqua's floor plan, construction, and context as a given, they explored the forms which would result from a design process focused solely on the practical concerns of solar shading and view, though this case study presents only the shading component of the research.

To negotiate the solar shading performance of the terraces, they developed a new tool called Shaderade, which integrates EnergyPlus simulations into the Rhinoceros parametric modeling environment, allowing the designer freedom to go beyond prescriptive shading approaches.

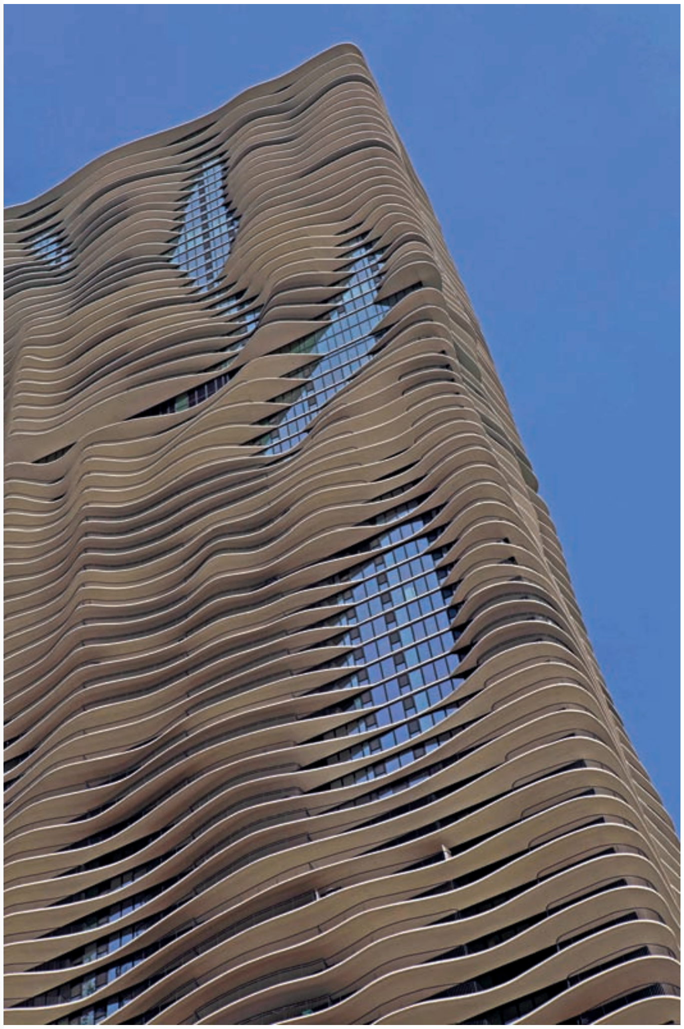
Simulation

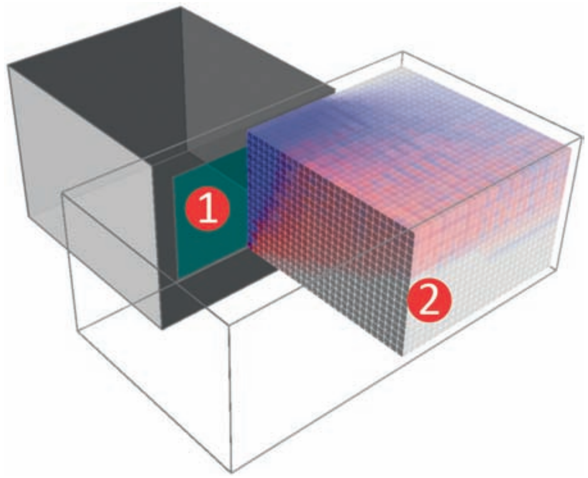
The usual approach to static solar shading is to create an overhang that completely shades the window during peak cooling season, often of uniform depth. However, any shading device will have an effect on energy use throughout the year, including a heating season if it exists. Determining the net benefit of a shade therefore requires calculating the effect on thermal loads for every hour of the year. This is a relatively easy task with current thermal simulation engines.

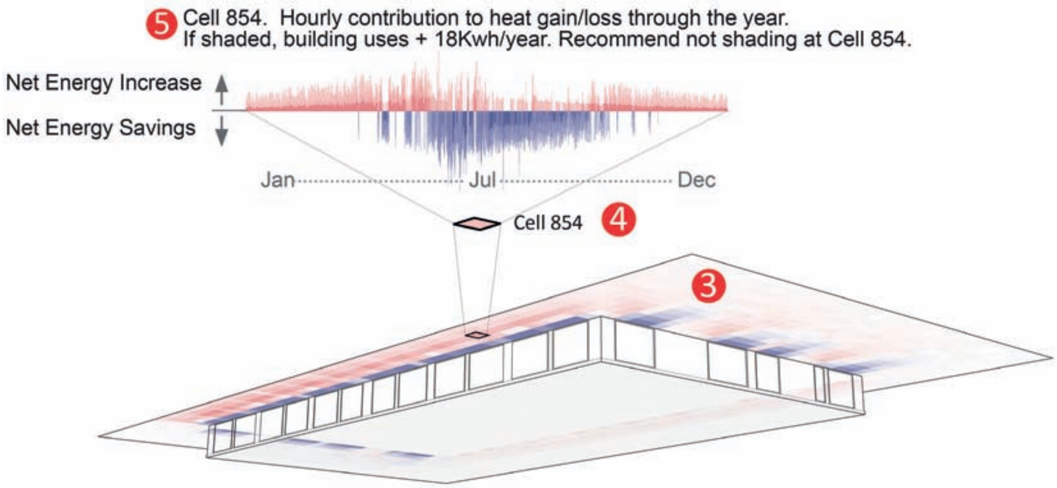
On a project with sinuous curves like the Aqua Tower, attempting to design thermally optimal overhangs would generally involve testing an enormous quantity of shading options for each floor to look for a winner. Depending on the number of parameters needed to define each terrace and the number of potential solutions tested for each parameter, it could take a single computer millions of years to exhaustively test all the formal possibilities for each floor.

In addition, the results would fail to give the designer any insight into which portions of a shade are most effective in reducing energy use. This means the designer could not react aesthetically or modify any piece of a preferred option without potentially invalidating the underlying energy performance that helped them select that option.

Testing done by an evolutionary solver can converge on an optimal solution more quickly than indiscriminate guessing, but still fails to provide the architects any guidance as to which portions of a shade matter most.







7.30

The Aqua Tower. The parametric aesthetic of the Aqua Tower was investigated using the Shaderade method of shading design.

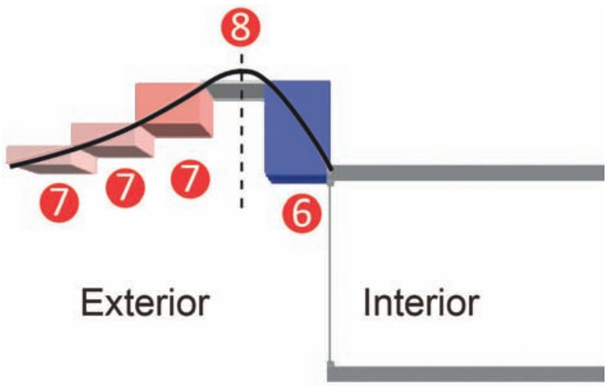
Source: Photo by Jeff Niemasz.

7.31

Shaderade Boston cube. Each colored cell shows net higher (red) or lower (blue) energy use if a shading device occupied its area.

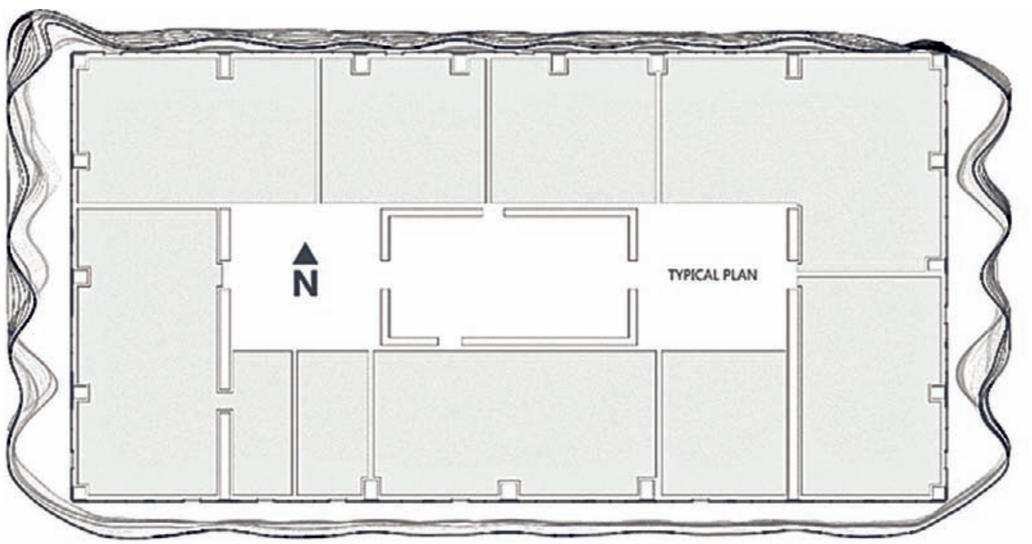
7.32

Section through a typical window, showing ideal shading device depth at the inflection point of higher and lower energy use.



7.33

The inflection point.



7.34

Plan view of optimized shading.

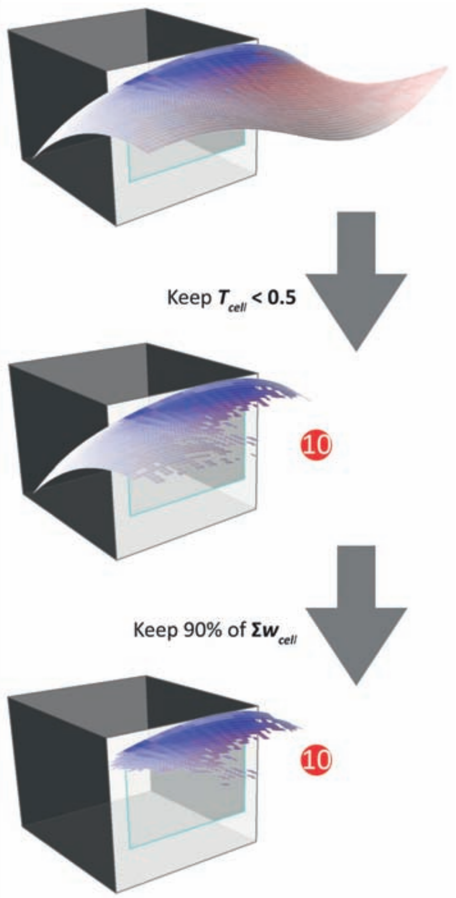
The Shaderade approach, which advanced earlier work by Eran Kaftan and Dr. Andrew Marsh, involves mapping the annual energy consequences of each position where a shade could affect energy transmission through a window (1) in two or three dimensions (2).

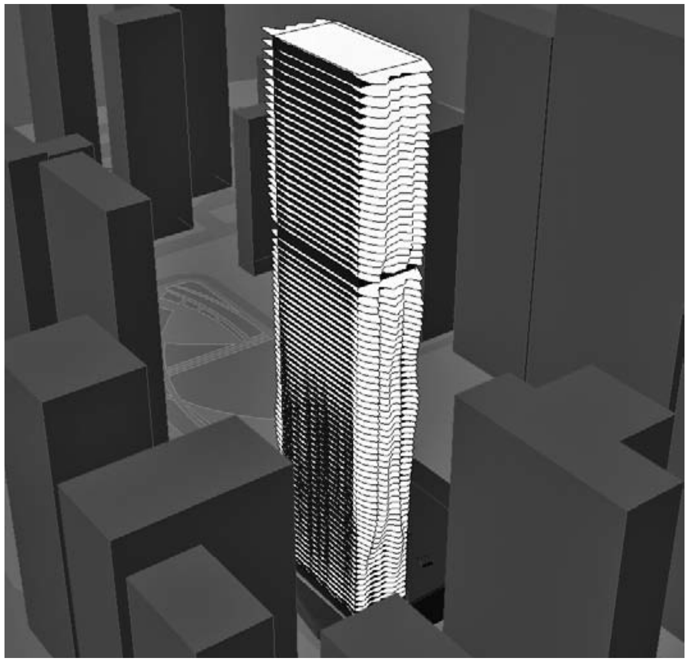
The method begins by running a single simulation of a building shaded only by context, which yields hourly information about thermal loads and heat gains transmitted through the windows from the sun and sky. The horizontal plane to be occupied by the shading device is then divided into many small pixels (3). In about a minute of run-time, Shaderade finds an energy-optimized shading form for a single floor and creates a map of the annual net effect on energy use provided by each portion of the shading plane (3).

The net energy effect of each portion of the shade (4) at each hour of the year (5) is predicted by combining the thermal analysis with any direct or diffuse solar rays that pass through that pixel and intersect any of the windows.

The pixels can then be ranked and aggregated to find a thermally optimal set. In the case of a horizontal overhang like the Aqua Tower, integrating the annual results for various shading device depths in section shows net energy use decreases (6) and increases (7). The inflection point (8) determines the optimum shading device depth. The resulting variation in shading depths can be simply applied in two dimensions (9), similar to the Aqua Tower aesthetic, it can be clipped to find an optimized shading shape in three dimensions (10), or it can be interpreted for aesthetic refinement.

This last option may be the most powerful, as the designer can simply look at the false colors to determine where a shading device may be beneficial, harmful, or has negligible effect on annual thermal performance, all in relation to a specific window, building, typology, context, and climate.





7.36

3D results of energy optimization using Shaderade. Many other variations are possible by weighting various parameters.

7.35

3D optimized shading, clipped to different parameters.

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While shading is traditionally considered as a function of climate, latitude, and orientation, however, urban context, internal loads, and fenestration patterns are equally important. Even without the shading caused by dense urban context, optimized shading would not be homogeneous because of variations in program, uses of each individual room, window locations and window sizes (10).

The original thesis considered view as well as energy, consistent with the stated intent of the Aqua Tower's design team, though any number of criteria could have been chosen to generate a form. The choice of each criterion and their weightings can be determined by the architect to help create buildings with exceptional beauty and performance.

The Shaderade method has been automated as a component for the Grasshopper plug-in for Rhinoceros and will be distributed in the future release of the Diva for Rhino software.

7.5 RENEWABLE ENERGY LOCATION + SIZING

Renewable energy is often the last and most expensive option in low-energy design. However, Net Zero Energy buildings often use available renewable energy to set energy goals near project inception. Using parametric modeling to study direct and indirect irradiation for specific panel sizes, orientations and angles can be used to optimize for total energy yield, most efficient yield, or to minimize overall renewable field size.

Project type:
6-story office building

Location:
Seattle, Washington

Design/modeling firm:
Miller Hull

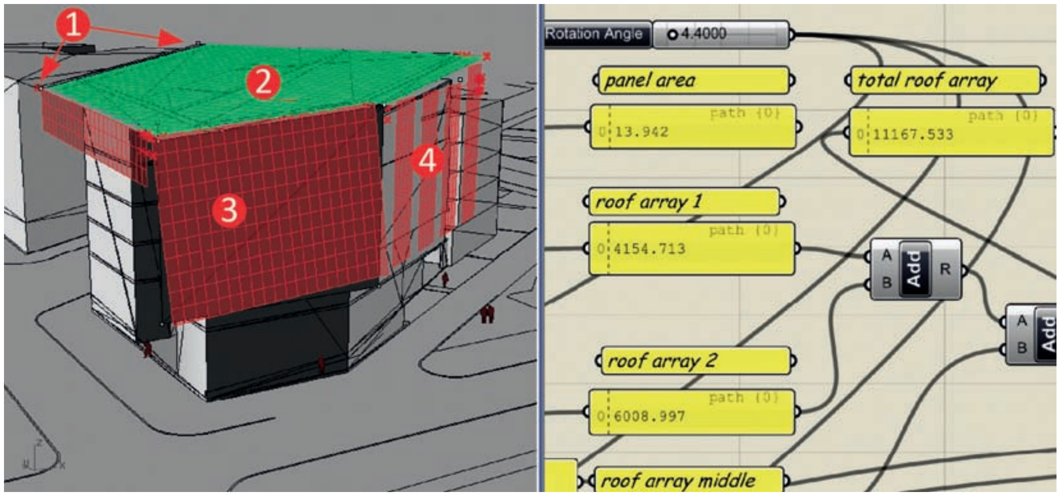
Overview

The 51,000 ft^2 Bullitt Center in Seattle expects to achieve Living Building status, and it will be the largest when certified. To achieve the Living Building Challenge's Net Zero requirement (which does not allow combustion) in the cloudy Seattle climate, the project required high-grade electricity from photovoltaics.

Design involves a nearly unlimited number of options. In this case, each photovoltaic (PV) layout needed to be quickly quantified since it set the overall energy target. The design team knew from the outset that there would be a large number of PVs required to meet the needs of the project, since it is a multi-story urban office building. This design simulation was used to discover the geometric solution that would maximize PV production on site. At the same time, the designers had to consider the effects of the PV array on shading, daylight availability, rainwater capture, and other project goals.

7.37

Rendering of the Bullitt Center looking northeast.



7.38

Photovoltaic array model and Grasshopper definition.

Initial calculations suggested that a rooftop array contained within the property lines would not be able to power the project. Fortunately, the urban site has no nearby buildings that would shade the roof area, though a tree in the park immediately to the south shades part of the southern façade. Other studies were used to show that the array did not adversely shade adjacent properties.

This analysis occurred during concept design simultaneously with the project team developing energy conservation measures as described in Case Study 10.7, including daylight studies that considered the effects of some of the PV layouts.

Simulation

The aim of the simulation was to define the PV arrays—including tilt, orientation, and panel spacing—that would provide the required electricity production. SketchUp was used to create an initial design model which was then imported into Rhino for its interoperability with Grasshopper. To balance aesthetics and function, Grasshopper definitions were set up for each point defining the edges and heights (1) of the PV array so they could be manipulated. The Grasshopper definition automatically spaced panel and array sections to avoid any panel shading an adjacent panel.

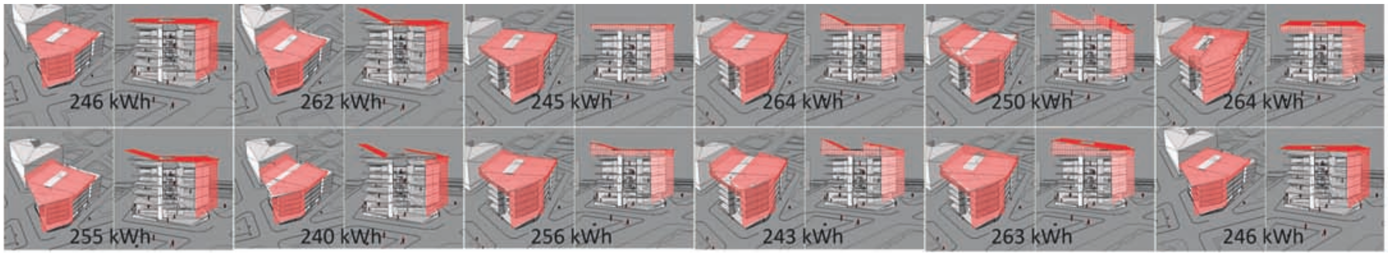
Once a configuration was established, the arrays were run through an Ecotect insolation analysis to determine estimated annual output. These estimates were also checked by the team's solar consultant and run through NREL's PV Watts estimating tool. Horizontal PV panels were simulated with a very high efficiency (19%). Vertically-mounted panels needed to be somewhat transparent for daylight and views from within the building, so the simulated panel had a lower efficiency.

Hundreds of configurations were initially studied, though after the first wave of analysis a best approach started to emerge. Results were evaluated by the design team and client in light of the energy and aesthetic goals.

This analysis culminated in choosing among the options to reach the minimum goal of 250 kWh set by the design team. Configurations included primarily a low-slope roof array (2), a vertically-oriented array facing south (3), and a vertically oriented array facing southeast (4), which was not continuous because of the need for daylight penetration on that façade. The bulk of the production is provided by the rooftop array, which slopes consistent with the site grade at about 5 degrees to the southwest.

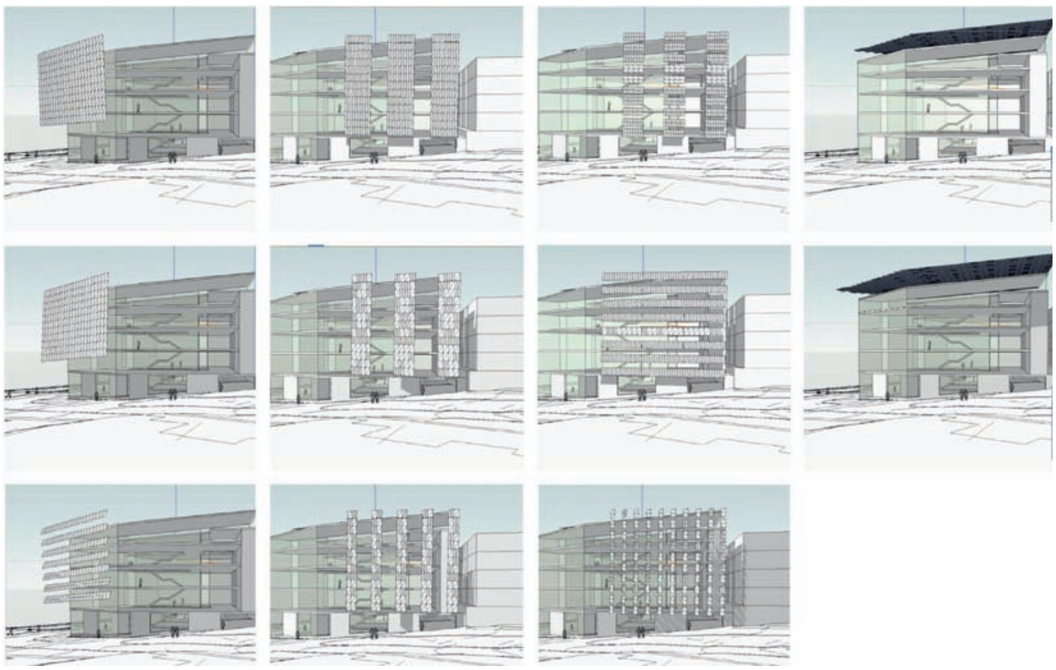
Some designs and orientations produced more electricity per panel, but included fewer panels with lower overall energy production. The target of Net Zero Energy required the total annual production to be maximized.

The original concept design program included a 42,000 ft^2 building with an EUI of 20 to 24 $kBtu/ft^2$, so annual production had to be at least 250,000 kWh per year, but preferably would be 280,000 kWh per year. Once the design was further developed, efficiency improvements allowed the design team to



7.39

A variety of options were tested, and each was associated with their total electricity production.



7.40

Each option was also studied for impacts on aesthetics and daylight into the office spaces.

lower the estimated EUI to 16. At the same time, the building grew to 51,000 ft^2. As a result, the building can be supported with only 230,000 kWh per year, which is the estimated output of the rooftop array only.

In the end, the configurations that were determined to be optimal for this project aligned closely with what had been suggested originally by the solar consultant—that the maximum production would be achieved from a flat, or near-flat, roof-mounted array, with no spacing between panels. This maximized the PV area and total production while only slightly reducing the output from each panel due to non-ideal panel tilt.

The projection of the rooftop array into the right-of-way was reviewed with the City of Seattle Technical Assistance Group early in the project. This group was supportive of the project goals and had been involved in the project from an early stage. In the end, the design team was able to show that the building was made as efficient as possible, and the only means to achieve Net Zero Energy was to place some of the array in the right-of-way. Later in the project, the developer obtained a permit for the right-of-way encroachment, similar to other owners obtaining permits for an awning, skybridge, or other large overhang.

The capabilities to do this work were developed in-house using the tools discussed. However, the architects worked in concert with the electrical engineers and the solar consultant to verify production estimates, and closely coordinated the energy balance at every step of the project with the other technical consultants.

7.6 EXISTING BUILDING SHADING STUDIES

Studying solar gain on façades of a complex geometric building can result in optimized shading strategies instead of a uniform, and more costly, universal shading requirement. A solar gain study can be done much more quickly and can be more accurate than performing a full energy model on each space.

Project type:
Lifestyle center

Location:
San Diego, California

Design/modeling firm:
Callison

Overview

Westfield, owner of the UTC Lifestyle Center in San Diego, hired Callison to oversee a major remodel which included energy efficiency upgrades. One of many energy-saving features was providing shading at storefronts to reduce solar load and increase comfort within each store.

San Diego has a pleasant climate with plenty of sunshine year-round, ensuring that many glazed retail spaces will become overly warm without proper shading. The client and project team wanted to identify storefronts that would be exposed to the most sun and require tenants associated with those storefronts to provide appropriate shading measures. Instead of simply requiring all storefronts to provide shading, or running an energy model for each tenant space, Callison proposed studying the amount of solar energy falling on each of the retail façades, with optimized shading recommendations based on the results.

Simulation

Westfield supplied Callison with a SketchUp model of the development, which was then imported into Ecotect. Glazed storefronts were subdivided into sensors grids for solar irradiation analysis. An annual

7.41

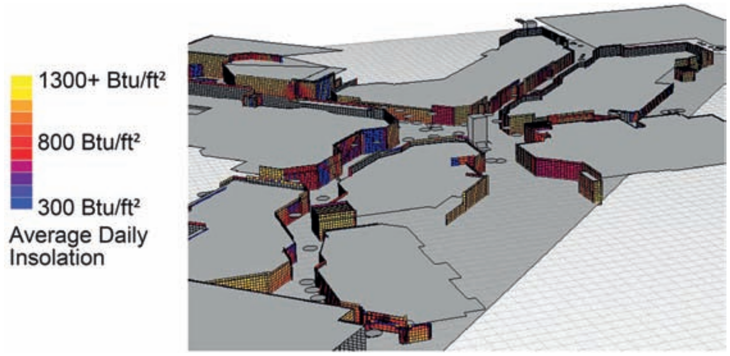
Rendering of Westfield UTC.

7.42

Ecotect Model showing solar irradiation on each façade.

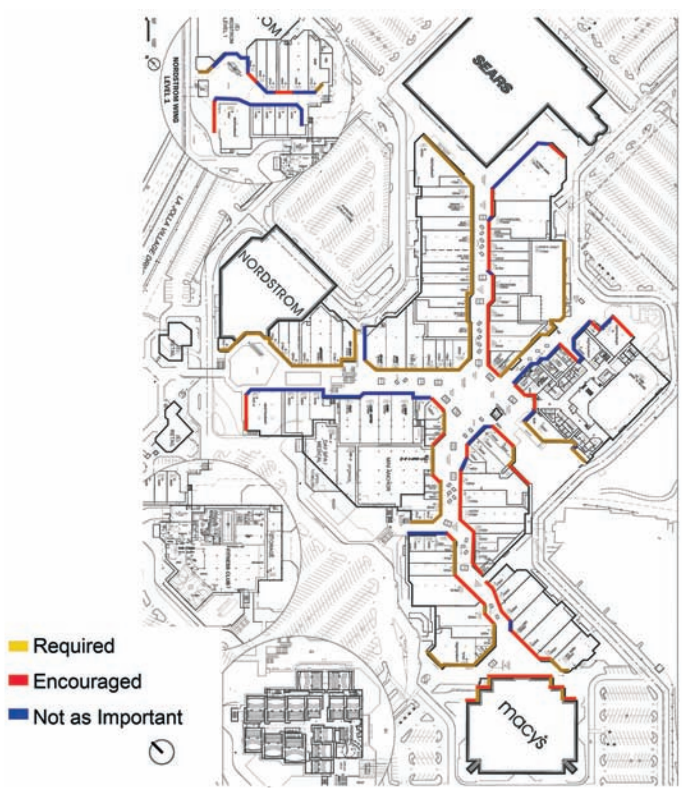
7.43

Plan showing importance of shading, included in tenant manual.



analysis was run to help determine which façades were most in need of shading, with the results being characterized as "average daily" irradiation to make the numbers more understandable.

The results were then interpreted graphically into three colors: façades outlined in yellow were required to have shading devices, those in red were highly encouraged to provide shading, and blue outlines were considered less important. The plan with color overlay was included in the tenant manual for their reference. Tenants generally appreciated this information on shading so they could design appropriately for their orientation.



8

Daylighting and Glare

Architecture is the learned game, correct and magnificent, of forms assembled in light.
—Le Corbusier

Nature is so powerful, so strong. Capturing its essence is not easy—your work becomes a dance with light and the weather. It takes you to a place within yourself.
—Annie Leibovitz

Light's importance to humanity cannot be overstated. Light is associated with divinity, knowledge, wisdom, honesty, and safety. Good design results in spaces and volumes that sculpt, shape, and color light. Daylight can be washed throughout a space to provide general illumination or brightness and movement.

Contemporary studies show these positive associations with daylight have measurable results—increased happiness, work performance, and retail sales. Other studies show that health is improved when we are immersed in the daily fluctuations of light and are visually connected to views and outdoor conditions:

- A study of 73 stores within a chain in California, of which 24 had significant daylight, found that daylight levels could predict sales as well as parking area size, number of local competitors, and neighborhood demographics; it was also associated with an increase in sales of up to 40%. This corroborated a previous study of a different retailer where an increase in sales of up to 40% was associated with daylight. Both of these chains used diffuse skylights to provide daylight (Heschong Mahone Group, Inc., 2003a).
- A study of 200 office workers who performed short cognitive tests at their desks found a correlation between performance and access to daylight (Heschong Mahone Group, Inc., 2003b).
- A study involving more than 8000 3rd–6th grade students found that student performance was as much based on window characteristics and daylight access as teacher characteristics, number of computers, or absentee rates (Heschong Mahone Group, Inc., 2003c).

Reliance on electric light has eroded architects' ability to correctly use daylighting. Architects are re-learning how to provide quality daylight and to reduce energy use associated with electric lighting, assisted by the use of design simulation. Many lighting designers use daylight analysis software, since the interplay of electric and natural light can create striking scenes and day-to-night contrasts. Since this book focuses on energy use, the energy savings associated with the correct use of daylight will be covered in the most detail.

Peak daylighting potential occurs at peak electric load times. Since lighting can be 20–40% of a building's electric loads, minimizing electric lighting use during peak cooling times can reduce the peak electric load of the building by nearly this amount, see Case Studies 7.3 and 9.1.

Daylight design and associated energy savings fail when glare is not mitigated. Five minutes of glare often inspire occupants to lower the blinds, which may remain down for hours or days, so excellent

8.1

Physical daylighting model of one floor of the Bullitt Center, designed by Miller Hull, under uniform sky conditions in the skybox at the University of Washington Integrated Design Lab.

daylight design also balances user operability with automation. Daylighting is successful when occupants prefer to have most of the electric lights off, saving energy.

This chapter describes methods of daylighting, provides the most common measurements of daylight and glare within buildings, provides guidance for computerized daylight simulations, and then illustrates each of the common measurement types with a case study.

THE SUN AND SKY AS LIGHT SOURCE

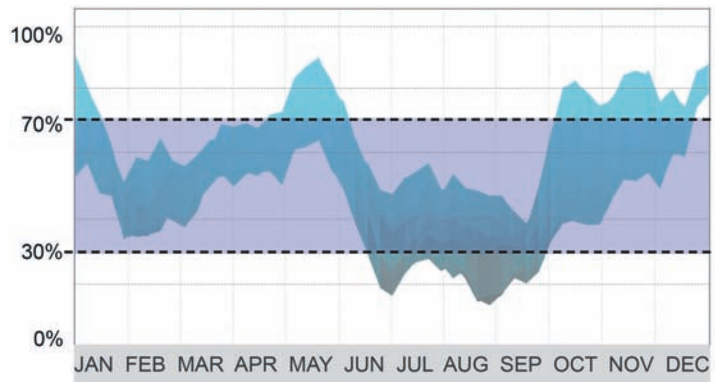
The sun is a challenging light source. Its angle and altitude in relation to a window or skylight constantly change throughout each day and season, requiring diligence to channel daylight without glare. Daylight is a combination of both direct light from the sun and diffuse light reflecting off the atmosphere, water vapor, clouds, and surroundings. On sunny days, the sun and sky can provide blinding light on one side of a building and not enough light on the opposite side, while clouds diffuse the light more evenly across the entire sky dome on overcast days.

The first step in designing and simulating for daylight is to determine the prevalent characteristics of the sky, referred to as the "sky condition" or simply as a "sky." In some seasons one sky condition will be dominant—overcast winters in Seattle or sunny summers in Phoenix, for example. The International Commission on Illumination (CIE, from the French acronym) defines the character of the following skies common in daylighting simulations.

In simulations each of these skies is defined by an algorithm that maps luminance levels onto an imaginary hemisphere, called a sky dome. Light from each point on the sky dome is projected onto a 3D model as part of a computerized daylight simulation.

- A *uniform sky* is the simplest sky condition, which assumes equal light levels from all points on the sky dome.
- A *clear sky* (or sunny sky) is used when cloud cover is below 30%. Clear skies can be approximated as having a 10:1 ratio of brightness from the sun to the rest of the sky, which drops off steeply near the sun. The clear sky is used for daylight availability calculations, among others.
- An *overcast sky* (or cloudy sky) is used when cloud cover is above 70%. Overcast skies contain roughly a luminance transition of 3:1 from the zenith to the horizon. For ease of calculation, most overcast skies do not consider the sun's position. The Overcast Sky is used for daylight factor calculations.

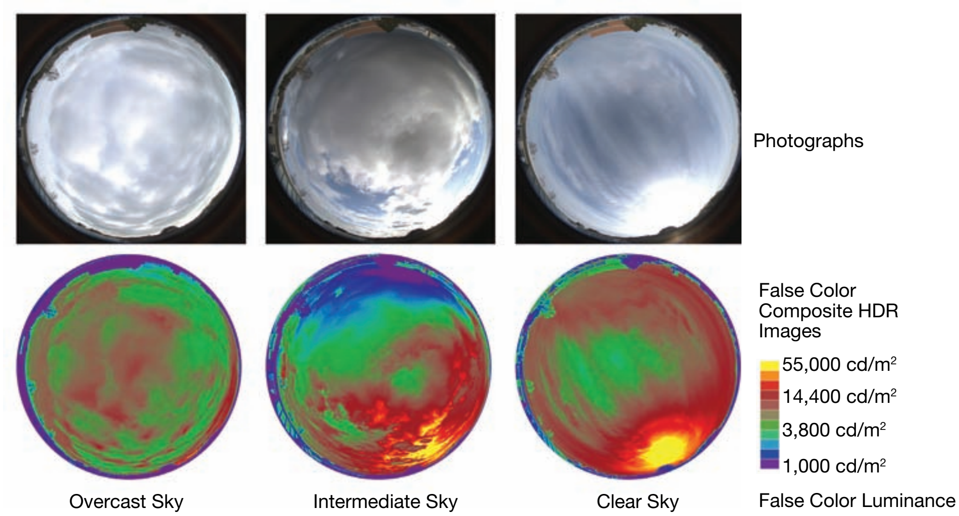
Daylighting designs that work well for the extreme conditions of clear and overcast skies will work under any conditions, so they are commonly used. Other sky conditions can be calculated from a weather file for more detailed analyses of daylight and glare levels; this is especially useful for annual simulations of



8.2

Cloud cover in Allen, Texas, varies from intermediate and overcast in winter, to intermediate and clear in summer. The CIE defines clear skies as >70% cloud cover, overcast skies as <30% cloud cover, and other skies as intermediate.

Source: Modified output from Autodesk Ecotect Suite. Courtesy of Callison.



8.3

Actual sky conditions that correspond to overcast, intermediate, and clear skies are shown using high dynamic range (HDR) fish-eye photographs and false color images. While most daylight simulation uses synthetic, averaged sky conditions, actual sky conditions vary by the minute. HDR skies can be used in daylighting simulations, see Case Study 8.6.

Source: Inanici (2010). Images © Illuminating Engineering Society, www.ies.org.

lighting energy use. In many cases, automated software will help select the appropriate sky based on the weather file. High dynamic range photography can also be used to create sky conditions as illustrated in Case Study 8.6.

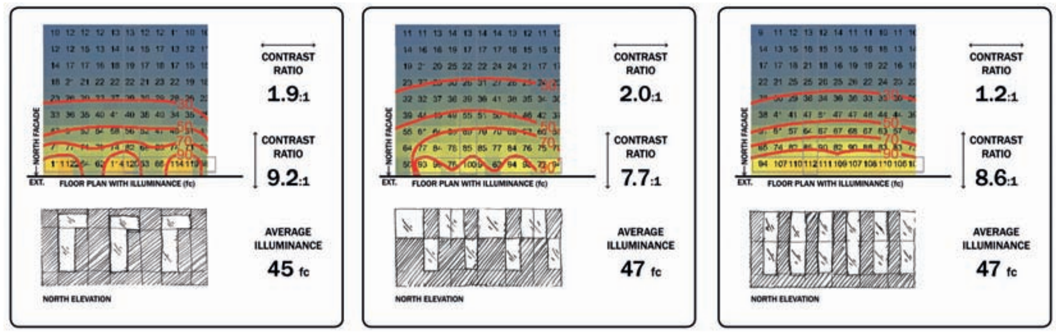
DAYLIGHTING DESIGN

Good daylighting begins with setting goals for each space, which can be done as soon as a spatial program is received. Each space can be considered for desired minimum and maximum light levels, hours of occupancy, preference for side-light or top-light, desired views, and sensitivity to direct light from the sun. Case Study 8.1 looks at two spaces within a school that have different lighting needs, for example. A program can also be diagrammed so that spaces with light affinity are placed in ideal locations for daylighting.

With daylight, the design team is looking for the sweet spot between achieving minimum illuminance levels, avoiding glare, balancing light levels within a space, optimizing solar heat gain and thermal loss through fenestration. The first three can be determined using simulations covered in this chapter, while the last two are handled with experience or energy modeling.

Most electric lighting designers are tasked with providing even lighting throughout a space, with some highlights for visual interest. Providing quantitatively even lighting through the use of daylighting is nearly impossible, especially with side-lighting. Instead, daylighting design is best when spaces provide at least minimum light levels, glare reduction, and visual balance.

The area within a building where electric lights can be turned off or dimmed due to the presence of daylight is called the daylight zone. A space's height, depth, and orientation are the most important



8.4

Plan-view studies showing illuminance levels for three window options on a north façade under overcast skies. The room's contrast ratios across width and depth are also shown, with lower contrast being preferable, but difficult to achieve, with side-lighting. Lighting designers typically include a room's contrast ratio in their studies to ensure even lighting throughout a space.

Source: Courtesy SERA Architects.

geometric aspects that define the daylight zone. For skylights, useful daylight will spread approximately half the ceiling height beyond the edge of the skylight in plan view.

For sidelighting, the daylight zone will generally be the depth equal to 1.5 to 2.5 times the window head height, or sometimes the first 15′ inside a façade. The electric lights in this area are usually on a single daylight sensor. Within a side-lit daylight zone there is a significant drop-off in light level from the window to the interior, so incorporating two rows of lights on daylight sensors can be more effective to minimize energy use. Light shelves reduce glare and provide more even daylighting levels near a window.

DAYLIGHT HARVESTING METHODS

Side-lighting

Side-lighting using vertical glazing is the primary daylight harvesting strategy in most buildings. Prior to 1940, most office, hotel, and residential buildings had narrow floor plates and tall windows to allow for plenty of side-lighting. Steven Holl referred to these as Alphabet buildings in *Pamphlet Architecture #5,* because in plan view they resemble 50–70 foot-wide letters. The daylighting logic behind Alphabet buildings can also be expressed by enclosing the area between wings with daylit atria.

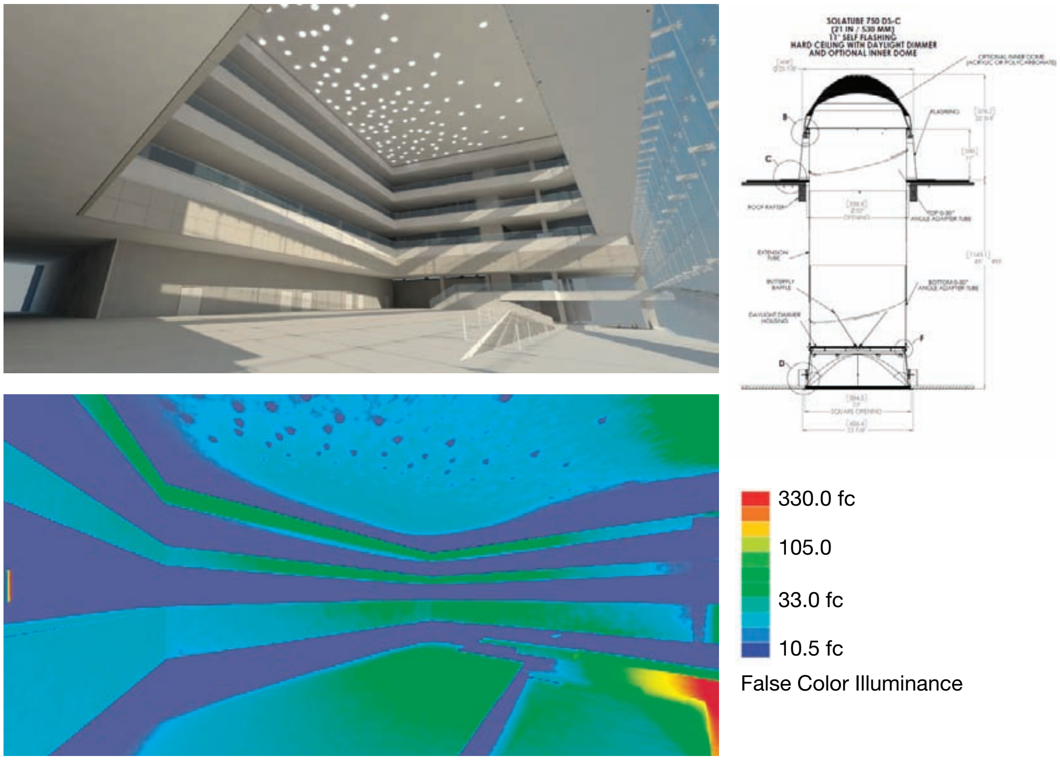
Interior daylighting levels from side-lighting include many factors: shading or reflection from adjacent trees or structures, exterior shading systems and light shelves, glazing properties, glare control such as blinds and shades, interior layout and furnishings, and interior colors. In daylight simulations, some of these will be drawn geometrically, while the project team must estimate the effects of others.

Glazed areas up to 7 or 8 feet above the floor are often considered "view" glazing, while areas above this are called "daylight" glazing, and used to allow daylight deep into a space. In some cases they contain different glazing properties, different blind operability, or light shelves at the intersection that prevent glare from the daylight portion at most sun angles.

Top-lighting

Top-lighting allows more creativity since roof geometries are expected to be playful and striking, as in Steven Holl's Saint Ignatius Chapel in Seattle. Much more light is available with top-lighting than with side-lighting, since the sky is generally brighter near the zenith than the horizon. Top-lighting is primarily used for high-ceilinged spaces such as atria, big box stores, churches, and warehouses. Louis Kahn was very successful at incorporating top-lighting into the Kimball Art Museum in Fort Worth, Texas.

Near-horizontal top-lighting systems can provide a view of the sky, but typically create problems of heat gain, heat loss, and glare. They are generally best for unconditioned or semi-conditioned spaces. Skylights with vertical glazing, called monitors, are much less prone to these problems since they can be oriented to block unwanted light and heat gain. Big box stores usually use translucent skylights, which diffuse the light for better daylight distribution and less floor-level glare; some translucent skylights also have better thermal performance than is possible with clear skylights. Studying geometry and glazing type through simulation can help the designer reduce glare and control heat from direct sunlight.



8.5

To balance light within an atrium with one glazed wall, LMN Architects studied an asymmetrical array of light pipes. Conversations with the manufacturer led to modeling each of them as a light source within a lighting simulation instead of attempting to use ray-tracing to predict light levels through them. A 3D view and illuminance image show even light distribution on all vertical surfaces, which serves to reduce contrast between the glazed wall and the interior walls.

Source: Courtesy of LMN Architects.

Historically, factories and warehouses were built with rows of vertically-glazed top-lights such as saw-tooth and monitors. Recently these daylighting strategies have been revived and incorporated into many high-performing buildings, such as the Roche Pharmaceuticals Lab designed by Skidmore, Owings, and Merrill in Case Study 8.7. Top-lighting apertures can also be used to drive natural ventilation. With simulation, creative forms can be tested for performance characteristics, incorporating translucency, opaque and transparent portions, and amorphous geometry to sculpt the right quantity and quality of daylight for each space.

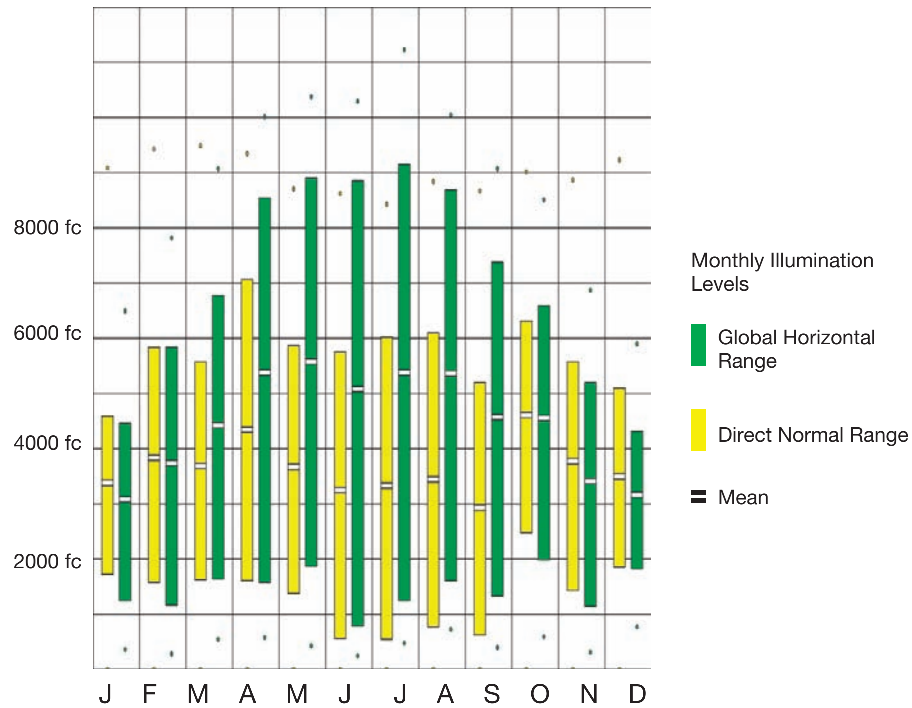
Other Methods of Daylight Delivery

Other daylight delivery methods are effective but more difficult to simulate correctly. *Daylight pipes* are tubes that deliver light from roof level to a ceiling fixture. They have a skylight at the top, mirror-like surfaces inside, and a diffuse "fixture" at the bottom. In many cases they include a dimmable lamp inside to maintain a minimum light output as daylight levels fluctuate throughout each day. Some daylight pipes also include a sun-tracking system to reflect direct sunlight into a space.

Fiber-optic fixtures have a sun-tracking mirror that reflects direct sunlight into fiber-optic lines. Fiber-optic lines can be curved around obstacles and through tight spaces, delivering daylight to spaces that otherwise could not receive it. Sun-tracking increases transmitted light levels by a factor of 10 or more on sunny days, but does not increase them significantly on overcast days.

Translucent façade and roof materials such as frosted glass, fritted glass, plastics, and translucent fabrics can provide diffuse light over a large area, such as the Denver International Airport or the Water Cube (the Beijing National Aquatics Center). Each of these can also be used as lightweight shading devices that allow some light through. Translucency is discussed in more detail later in the chapter.

Manufacturers are often willing to assist a design team in simulating light pipes or other specialty products, though a background in daylight simulation is necessary to successfully incorporate their information. Other manufacturers will perform simulations for free or on an hourly basis.



8.6

An output from Climate Consultant software shows the range of monthly outdoor illumination levels in Atlanta, Georgia, from a TMY3 weather data file.

Source: Courtesy of Callison. Courtesy of UCLA Energy Design Tools Group, http://www.energy-design-tools.aud.ucla.edu/.

MEASURING DAYLIGHT

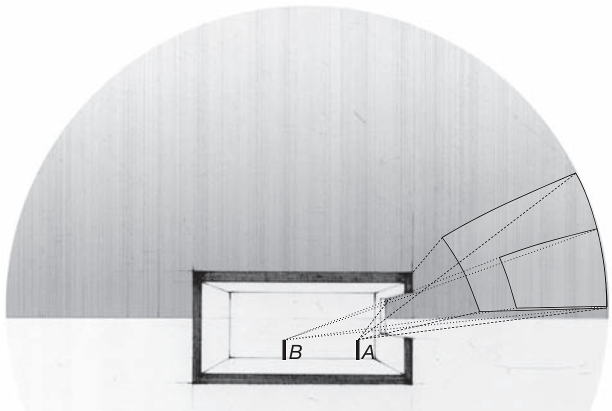
Solar irradiation power on a surface is measured in Btu/h/ft², covered in Chapter 7. Solar irradiation contains infrared, visible, and ultraviolet light, see Diagram 6.5. The visible spectrum is between 380 (violet) and 680 (red) nanometers in length, making up less than half of the power within sunlight. Within the visible light spectrum, human eye sensitivity to light peaks around 550 nanometers (green and yellow) and drops off towards either end of the spectrum.

This means that light is related, but not equivalent, to heat. Converting the amount of heat (usually in Watts/ft² for lighting) to useful daylight (Lumens/ft²) requires a mathematical operation called the luminosity function, which is based on typical human sensitivity to each wavelength.

Lumens are used to measure light output. For example, a 60-Watt incandescent, a 15-Watt compact fluorescent and a 13-Watt LED lamp may all output around 800 Lumens. The ratio of Lumens to Watts (or Btu/h) from a given light source is called *luminous efficacy*. The sun and sky deliver much more light per unit of heat (efficacy of 100–150 Lumens/Watt) than most electric light sources (10–100 Lumens/Watt), meaning that daylighting delivers more light with less heat than most electric light sources. Confusingly, electric light efficacy can refer to the ratio of input power to light output, or the amount of heat associated with the light output.

Illuminance, measured in Lux (Lumens/m²) or foot-candles (fc, Lumens/ft²), is the amount of light falling on a surface. It is used by lighting designers and building codes to quantify light levels and estimate light balance across a space. One cannot see illuminance, but it can be measured with a light meter. Illuminance values for outdoor conditions are in the neighborhood of 2,000 fc and 10,000 fc on cloudy and sunny days, respectively. A wide variety of indoor illuminance minimums are published; for an office they are generally between 25 and 50 fc. In most lighting simulations 1 fc is assumed to be equal to 10 Lux, even though the ratio is 1:10.76.

Luminance is the perception of light's brightness based on the quantity that can be calculated to enter our pupils. This involves calculating the angle from the light source or reflection to our pupil's aperture. Since the aperture of our pupils constantly adjusts, absolute luminance levels are not as important as relative luminance levels. Angular measurements are done in steradians, so the perception of light is measured in Lumens/m²/steradian, commonly referred to as candelas/m² (cd/m²). The sun's luminance



8.7

Daylight factor is based on the amount of indoor light as a percentage of outdoor light levels. Using a CIE overcast sky, it reports the percentage of outdoor light that arrives at a given point. Point A has access to significantly more sky than point B, with a proportionally higher daylight factor.

Source: Illustration by Amal Kissoondyal.

may be measured as high as 1,600,000,000 cd/m^2, whereas most indoor luminance levels are between 100 and 5000 cd/m^2.

Luminance depends on the illuminance of a surface as well as the materiality: specularity (the opposite of diffusion), reflectivity, color, transparency, and other qualities. Luminance values are useful when assessing the light quality of a space, including measuring glare.

A photograph is a luminance image. Photographs are not very useful for daylighting design purposes; although they contain relative luminance information about a space, they are generally not calibrated to human visual sensitivity. High dynamic range (HDR) photography combines multiple shutter speeds from the same vantage point to map absolute luminance values that are useful in daylighting design. They can be used to analyze a physical daylighting simulation as in Case Study 8.4, or to generate a sky condition as shown in Case Study 8.6. Luminance can also be measured using a Spot Photometer, though this is cumbersome.

Daylighting analyses are often done early in the design process with simple models that exclude furniture. A project team may account for this omission of geometry by increasing the minimum and maximum light levels by up to 100%. For instance, in simulations of the Austin Central Library, Case Study 8.3, the minimum light level desired was 300 Lux, but the simulation threshold and false color scale were set to a minimum of 500 Lux to account for the lack of 3D furniture in the simulation. Since luminance and illuminance are confusingly similar words, the author has found it useful to remember that illuminance ‘illuminates’ a surface.

WORK PLANE ANALYSES

The most basic criterion for lighting design is to meet minimum illuminance levels at the work plane, often defined as a horizontal plane 30″ above the floor. Reading, writing, food preparation, and many other tasks that require lighting are performed at this approximate height. Daylighting design, especially from side-lighting, has inherent contrast across the work plane from the façades to the interior portions of a room. Good daylighting design minimizes this contrast.

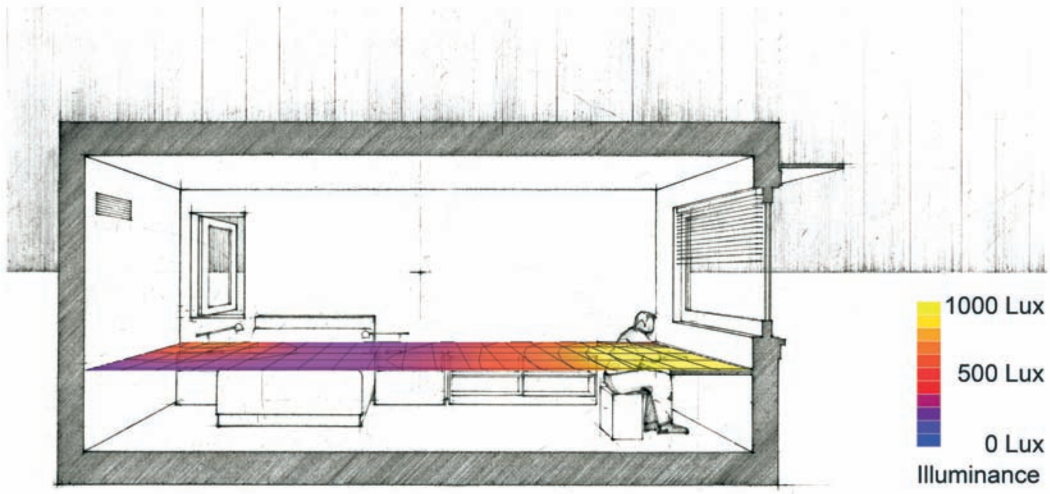
The most common ways to measure light levels at the work plane include the following.

Point-in-time

Point-in-time (PIT) illumination over a work plane can be used to investigate and compare minimum and glare-causing light levels at specific times of the day, and under various sky conditions, often used to study and improve extreme conditions. For example, a west-facing space may be tested on December 21 at 3 p.m. under a clear sky, when the sun is low and likely to cause glare.

Daylight factor (DF)

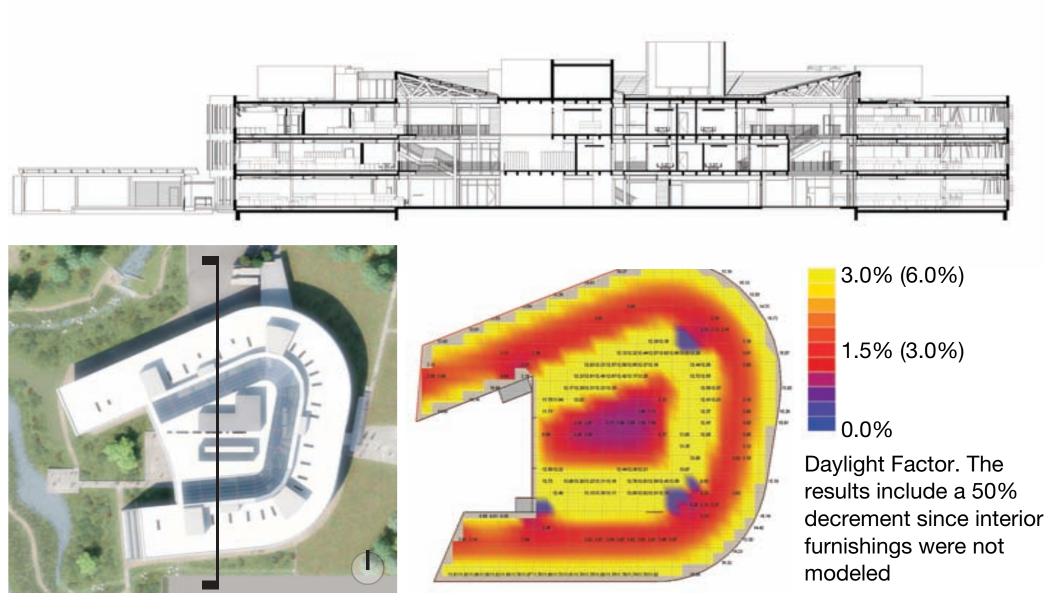
The *daylight factor* (DF) is the ratio of outdoor illuminance (measured horizontally) that finds its way to a horizontal sensor point using the CIE overcast sky or under a uniform sky created by a light box.



8.8

False color illuminance levels for 2 p.m. on March 21 at a work plane height of 30″ above floor level show that the majority of the space is at or above 250 Lux, meaning the space is well daylit and likely needs no electric lights to be on.

Source: Autodesk Ecotect output of Radiance data overlaid on an illustration by Amal Kissoondyal.



8.9

Federal Center South, Building 1202, is a 60′-wide office plate in the form of a U-shape around a daylit atrium. The false color results of a daylight factor simulation on the ground floor show good daylight based on sectional properties, including: office plate width, skylight geometry and glazing properties.

Source: Courtesy of ZGF Architects LLP.

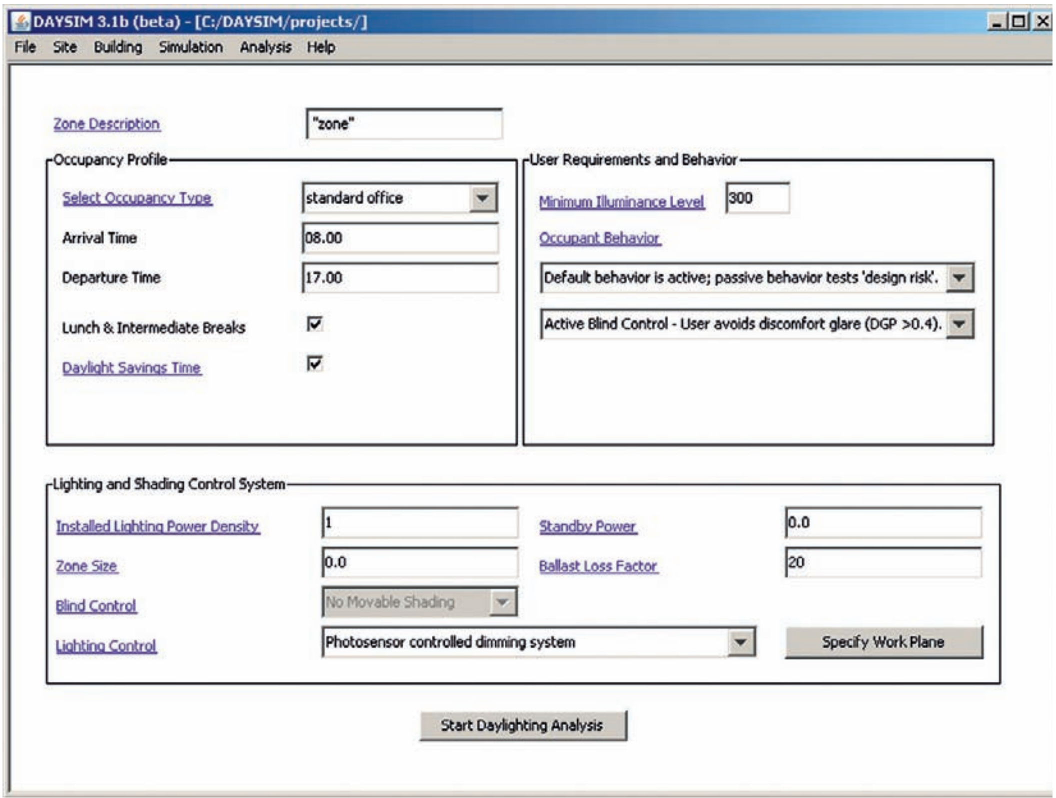
The daylight factor is independent of orientation and time of year, though it may take into account adjacent buildings and shading devices if the simulator chooses to include them. An office is considered well daylit with a DF between 2% and 5%.

In many cases, contrast glare is due to the difference between indoor light levels and outdoor light reflected off the ground or buildings; since daylight factor is a ratio of indoor to outdoor light levels, it inherently considers this type of glare, while most other metrics do not.

The daylight factor tends to over-predict top-lighting levels and under-predict side-lighting levels, but provides a quick, useful analysis for early design simulation in primarily overcast climates. When this type of calculation uses a clear sky condition, it is called *daylight availability*. For an example, see Case Study 8.1.

Daylight Autonomy (DA)

Daylight autonomy (DA) is an annual simulation that measures the percentage of occupied time that a sensor point within a building meets the minimum illuminance levels. The results can be coordinated with lighting and blinds schedules for shoebox or full energy modeling, discussed in Chapter 10. Sky conditions for each of the occupied hours in a year are approximated by combining climate data with the annual sun path.



8.10

Daysim software, that estimates daylight autonomy, has a user-inputted minimum lighting threshold, generally the illuminance level recommended for electric lighting. The characteristics of the occupants, the hours of operation, and other information are necessary to accurately estimate when electric lights may be dimmed or off on an annual basis.

A given sensor that reports a DA of 75% means that electric lights would not be necessary at the sensor during 75% of the occupied hours each year. DA presents a best case scenario for lights to be dimmed or off, since glare may cause blinds to be deployed, reducing light levels at the sensor. DA software requires the input of various assumptions about the building or users' operations of blinds as described in Figure 8.10.

Designing for 100% DA can be a useful goal for top-lighting with deep skylights as shown in Case Study 8.2. However, designing for 100% DA in side-lit environments often leads to over-lighting, glare and blind closure.

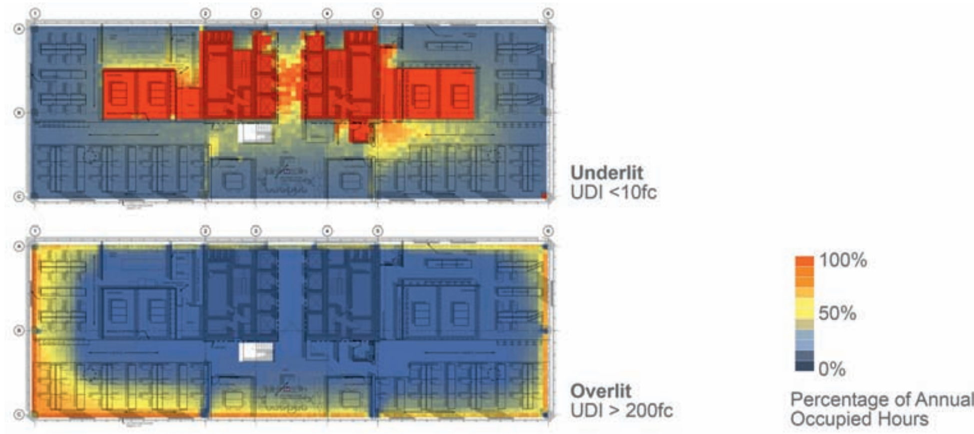
The daylight autonomy family of metrics includes many definitions of what is "successfully" daylit. However, the simulator can input any minimum threshold for the DA lighting calculation. The Illuminating Engineers Society of America (IESNA) considers a space adequately daylit when it is above 300 Lux for 50% of the year. Daylight autonomy metrics are often written with subscripts for the input parameters, for example, spatial daylight autonomy will sometimes be written as $sDA_{300/50\%}$ referring to 300 Lux for 50% of the year.

- *DAmax*: Daylight Autonomy can be run with a specified maximum illuminance level value that is assumed to create glare. Daysim defines DAmax as 10 times the desired minimum illumination level.
- *Useful Daylight Illuminance* (UDI) separates each occupied hour of the year into one of three categories for a given point in space, with each reported as a percentage of the year.
  - useful daylight, illuminance between 100 and 2000 Lux;
  - potential glare, illuminance greater than 2000 Lux (UDI >2000);
  - under-lit, illuminance below 100 Lux (UDI <100).

In practice, the ranges should be modified for each project based on desired minimum and maximum lighting levels. For example, in Case Study 8.8, useful daylight is considered to be between 300 and 2500 Lux.

8.11

LMN's office space was tested for areas that were underlit or overlit using the Useful Daylight Illuminance metric with illuminances below 10 fc considered underlit, while areas over 200 fc considered overlit. The percentage of each occupied hour of the year that is underlit or overlit is shown in false colours.



- *Continuous Daylight Autonomy* (cDA) analyses are similar to DA analyses, but also award partial credit when sensors are partially daylit. For example, a sensor point that receives 10 fc instead of the minimum 20fc over a given time-step would receive half the credit for that time-step. For spaces that have dimmable or stepped electric lighting or task lights that can be used when daylight levels are below the minimum, cDA can be a useful metric.
- *Spatial Daylight Autonomy* (sDA) is a very simple metric that returns the percentage of an entire space that achieves 30fc for 50% of the year. This threshold means enough daylight is being provided to result in electric lights being off for around half of the year, and dimmed through other parts of the year. Like UDI, the thresholds should be set for each space according to the intended use and lighting goals.

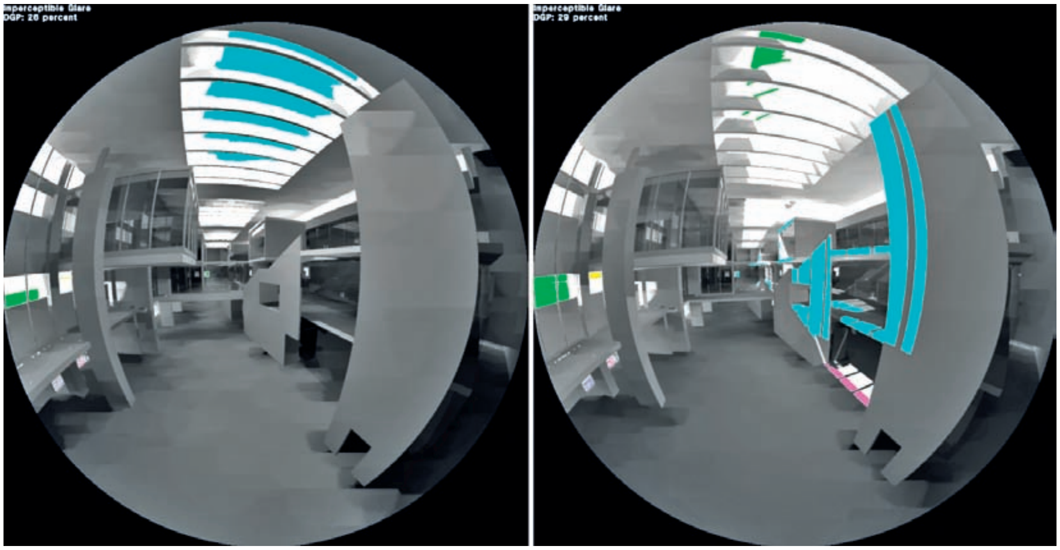
3D-VIEW ANALYSES

Three-dimensional analyses show daylight qualities and quantities for a specific date, time, and sky condition. Each pixel contains an exact luminance or illuminance value in Radiance renderings, while Daylight Glare Probability (DGP) and other glare detection metrics use advanced study-correlated algorithms to predict glare and map it visually onto a 3D rendering. Various overlays can be used to highlight characteristics of daylight within the view, including false color images and contour bands. See Case Study 8.7.

There are three common ways to render light in three dimensions:

- A *luminance image* is a computer rendering that shows accurate luminance levels (brightness), including reflections off objects. These generate perspectives where each pixel has an absolute luminance value, meaning that it can be compared against standards for contrast in determining glare. For an algorithm-based glare determination, see Daylight Glare Probability below.
- *High dynamic range (HDR) photography* creates a luminance image similar to a computer-generated luminance image. They can be used to analyze physical models (Case Study 8.5) or to create a luminance map of the sky (Case Study 8.6).
- Though it looks realistic, a computer-generated *illuminance image* shows how much light falls on each surface instead of the light reflecting off each surface. It is useful to see where and how much additional light is necessary to achieve minimum light levels and visual balance on walls, ceilings, and floors in daylit spaces, and it can also be helpful in determining where glare is likely. See Case Study 8.5.

Light may also be studied using *animations*, which combine the accuracy of point-in-time simulations with the element of time.



8.12

Daylight glare probability studies of atrium skylight options using DIVA software shows .26 and .29, both considered imperceptible glare. Each area within a field of view that contributes to glare is assigned a random color to show its location.

Source: Courtesy of SERA Architects.

GLARE ANALYSES

Glare occurs when a field of vision includes high contrast in luminance levels, especially when high contrasts are adjacent or the brightest area is large. Measurements of glare, like thermal discomfort, are self-reported, and thus are partially based on an individual's characteristics. For this reason, glare is often described as potential or probability, based on average responses by occupants in studies.

Glare can be caused by the following:

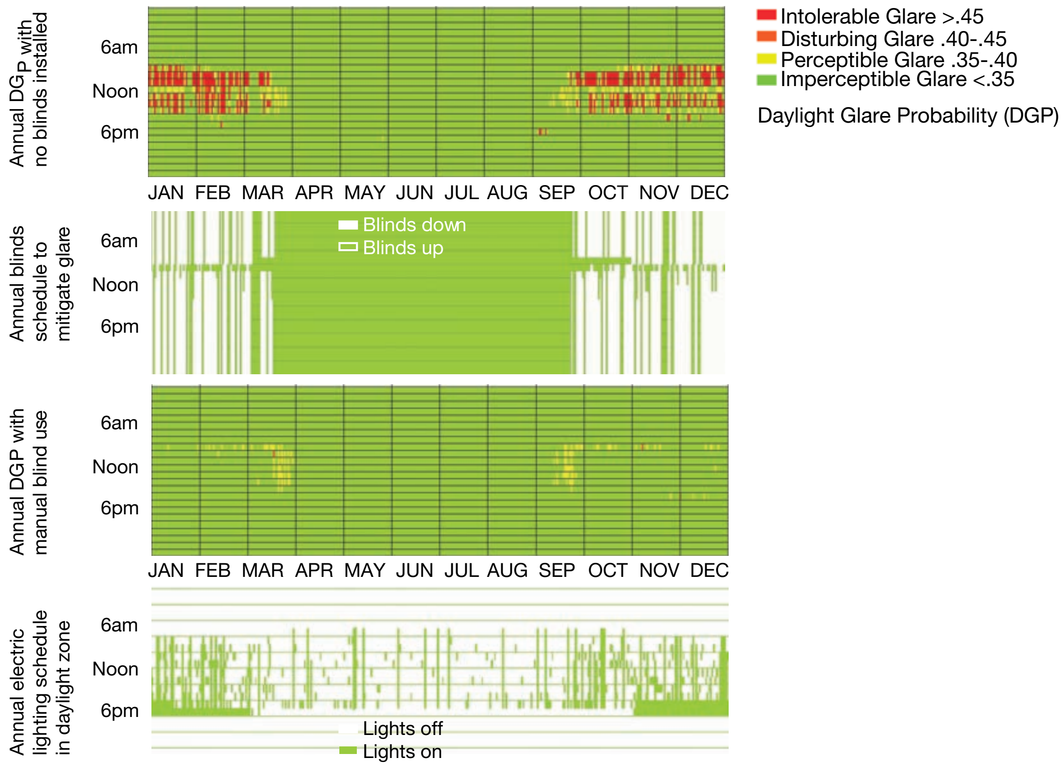
- Light sources without diffusion, such as the sun or a bare light bulb.
- Reflections from highly specular surfaces, such as a mirror, a polished floor, or a computer screen.
- Adjacent surfaces with significantly different luminance levels, such as a window frame in direct sunlight adjacent to a dark wall.
- Bright light diffused through translucent glazing products in an otherwise dimly lit room.

The biggest impediment to daylight-driven energy savings is a combination of temporary glare and a lack of understanding by building occupants of the role they can play in comfort and energy use. Blinds are often manually closed to block a few minutes of glare and left down all day or week. Since lights would otherwise be off, this means glare can significantly reduce modeled lighting energy savings and increase annual and peak cooling loads. These energy savings are more often achieved when the design team considers how glare can be mitigated while still providing daylight.

Design teams address glare within a daylighting design using a combination of orientation, glazing properties, blind operability (especially where the top blinds rotate independently from the bottom), automatically retracting blinds or shades, exterior shading devices, vegetation, and light shelves. Each of these can be simulated for their effects on lighting and energy use.

Most windows have a form of operable solar control—drapes, blinds, or shades. These can be operated manually or tied into a building's systems. They have a sometimes conflicting role as part of the lighting system, the solar heating system, and the thermal comfort system. Operable window treatments and user behavior are covered in Chapter 3, Comfort and Controls. Most see-through shades are dark in color so the shades do not glow, which would obscure the view outside.

Translucent materials and frits can provide some glare control from direct sunlight as well, though they can cause glare themselves since they diffuse daylight. For example, when 6,000 fc of outdoor light falls on a translucent window with nearby indoor conditions are around 50 fc, the window may be 30 or more times brighter than the room, causing a large area of potential glare.



8.13

An east-facing viewpoint within a south-facing office space experiences glare primarily during times with low-angle sun in the Fall and Winter. Diva for Rhino software creates a blinds schedule to minimize glare, based on research of building occupants' tendency to lower them based on glare but raise them infrequently, per the Lightswitch model (Reinhart, 2002). The blind schedule helps create a lighting usage schedule that can estimate lighting energy use savings to compare design options.

Source: Courtesy of Jeff Niemasz.

Glare is generally determined from a specific viewpoint and view direction. In many cases a person can turn their head or move to avoid glare; however, in some environments such as offices and hospital beds, occupants have little control over their position and orientation. While the metrics described here simulate glare from a fixed position, the concept of an adaptive view angle had been proposed that accounts for an occupant having some possibility of adjusting their predominant view angle (Jakubiec and Reinhart, 2011).

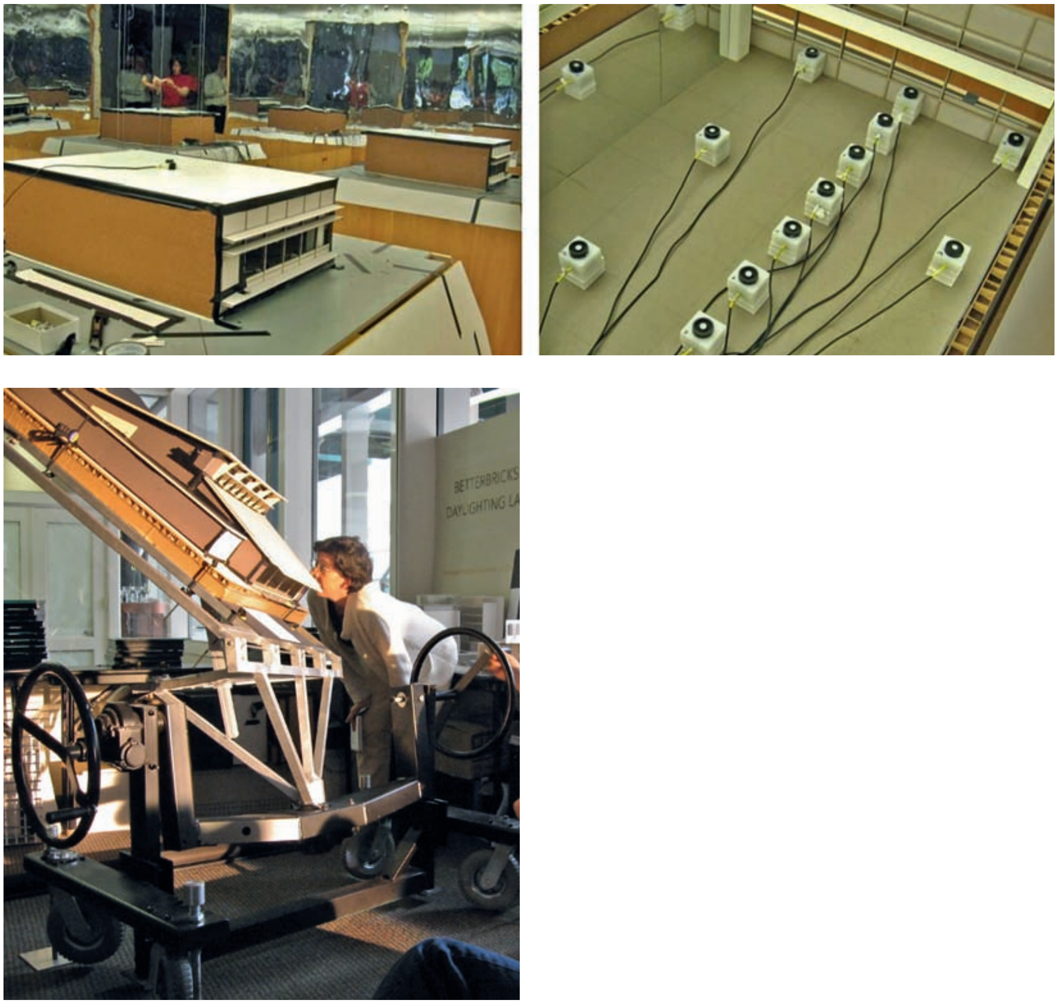
There are many algorithms that attempt to define the subjective experience of glare. Both DIVA and OpenStudio software incorporate user-located glare sensors with view angles to estimate blinds' use. The glare sensors act as occupants' eyes; when the glare reaches certain thresholds, blinds and shades are closed.

Daylight Glare Probability (DGP)

Daylight glare probability (DGP), created by the Fraunhofer Institute, evaluates a 180° fish-eye view and returns a single number to describe an entire scene for glare potential. The number assigned to a scene may be less than .35 (Imperceptible Glare) between .40 and .45 (Disturbing Glare), or greater than .45 (Intolerable Glare). DGP is calculated from a specific viewpoint for a given date, time, and sky condition. It rates the potential for glare based on high contrast in luminance levels in immediately adjacent areas, the size of contrasting fields within a scene, a slight weighting towards light around the work plane, and some other weightings.

Annual Daylight Glare Probability

Annual daylight glare probability is a new metric that calculates DGP for each hour (or other time-step) of the year. The output allows a quick visualization of the most glare-prone times of the year, plus a summary of the amount of time that each type of glare is present. The output is an annual schedule of when blinds would be deployed. Since lighting is often turned on when blinds are deployed, it can be synchronized with a Daylight Autonomy analysis to get a much more accurate idea of annual lighting energy use and associated heat loads. Case Study 8.8 uses Annual DGP.



8.14

A physical daylighting model showing use of light meters to calculate the daylight factor. An overcast sky is simulated by the light box, which has highly reflective ceiling and walls to create uniform light levels.

Source: Courtesy of SERA Architects.

And a physical daylighting model showing use of a heliodon at the Energy Studies in Buildings Laboratory in Portland, Oregon, to predict daylighting levels under sunny sky conditions. The large wheels rotate the model through specific solar angles in relation to a bright electric light.

Source: Courtesy of SERA Architects.

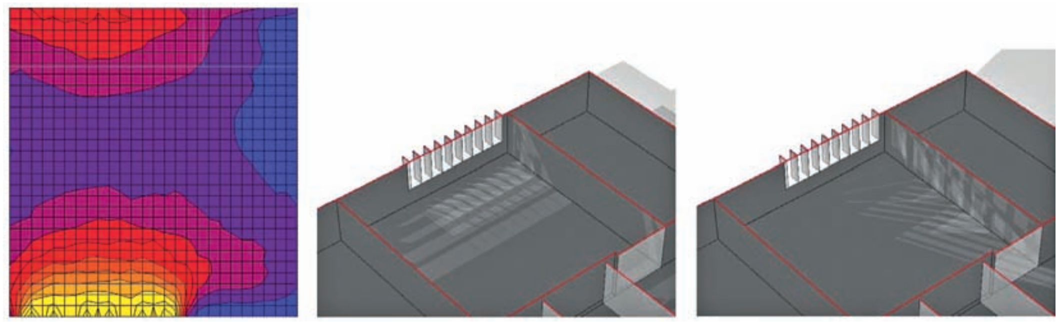
Annual Sunlight Exposure (aSE)

Annual Sunlight Exposure (aSE) is a simplistic measurement that approximates direct glare annually: it measures the percentage of a work plane area that receives over 250 hours of direct sunlight in a year, with direct sunlight generally being defined as greater than 1000 Lux. aSE does not consider the range of objects that may provide glare, assumes that blinds are never deployed, and does not include direct sun glare or light from reflections within a space.

PHYSICAL AND COMPUTERIZED DAYLIGHT SIMULATIONS

While most analyses in this book favor computerized simulations, point-in-time daylighting simulations can be done effectively with physical models. Since a camera or person can move around the model, the experiential qualities of daylight can be shared with others, enabling real-time discovery and group decision-making. Conversely, computer models must have each viewpoint rendered separately, a time- and processor-intensive operation. Physical models also are more accurate in predicting light's reflections: light does not behave differently at 1/2″ = 1′0″ scale than full size, for example, while computerized daylight simulations' need to reduce run-time can result in scaling issues.

Physical models use heliodons to simulate sunny skies and skyboxes to simulate overcast skies. Actual outdoor conditions can be used for physical models as well. Unless a heliodon is very large, only portions of a structure can be tested. A skybox has highly-reflective walls and ceiling, with diffused ceiling lights to create nearly uniform light levels. Many universities and research institutions keep these tools available for architects' use.



8.15

Plan view and axonometric views of a classroom. The daylight factor can be combined with shadow range analysis to quickly estimate locations of direct glare potential throughout a day or month.

Source: Autodesk Ecotect Shadow Range output and output of Radiance illuminance analysis. Courtesy of Mahlum Architects.

COMPUTER DAYLIGHT SIMULATION TERMINOLOGY AND CONCEPTS

As architects build 3D computer models more frequently, it becomes easier to integrate computer daylight simulations into the project workflow. Although in many cases models need to be simplified or re-built to reduce the run-time of daylight simulations, the techniques of 3D computer model building are more becoming familiar to architects, enabling purpose-built daylighting model geometry to be created and modified more quickly.

The simplest form of light and glare analysis can use any 3D software with shadow-projection capabilities. This can be used as a quick assessment of direct glare from the sun, but it ignores reflected light and glare. In some software, shadows from multiple hours can be displayed simultaneously to understand the range of shadows on a given day.

Accurate daylight analysis simulates light coming from all parts of the sky. In the software, sky conditions are defined by an algorithm that assigns relative luminances to various points on the sky dome. This algorithm can be combined with weather file illuminance measurements to create absolute values. The luminance values from this map shine onto surfaces and into buildings as part of a daylight simulation. Weather files do not contain information on cloud locations, so computer-simulated skies use averaged data or probable cloud locations.

Evaluating a design using computerized daylight simulation requires an understanding of and sensitivity to material properties, and proper training to correctly input and interpret a simulation. Most daylighting Graphical User Interfaces (GUIs), such as Diva or Rhino, include standard material properties that are appropriate for early design simulations.

Reflections

Reflections introduce significant complexity into computer-based software. In the physical world, light is partially absorbed by each surface it falls on. The rest of the light reflects (or bounces) in a number of new directions that eventually touch other surfaces. In this way the light of each subsequent reflection decreases until the energy is completely absorbed. Although the accuracy is decreased, computer simulations limit the number of times light is allowed to bounce, since each bounce adds significantly to run-time. For early design, between 3 and 6 bounces is usually sufficient.

The ratio of light that is reflected off a material is described between 0 and 1, with a mirror being close to 1 and a dull black object being close to 0. Color is an important factor; a stark white wall's reflectance will be around .75, while a bold red may reflect .30. Paint manufacturers sometimes list the reflectance of each color.

Light may reflect primarily in one direction, or it may diffuse into nearly all directions equally. The concentration of the reflected light is called *specularity*. Specularity is a ratio that ranges from 0 (perfectly diffuse, with light bouncing equally in all directions) to 1 (perfectly specular, with light reflecting only in one direction). Velvet is close to 0, while a mirror is close to 1.

Visible transmittance (Tvis) is the percentage of light that passes through an object, and is discussed in Chapter 6. *Translucent materials* are assigned an additional number to describe the portion of the light that passes directly through the glass without being diffused. Most translucent materials, including frosted and etched glass, only diffuse a small portion of the light. Some product manufacturers claim a higher diffusion rate, which would provide less glare and better light distribution.

As an example of software intricacies, EnergyPlus software assumes translucent products will perfectly diffuse the light in all inward directions. However, no translucent glazing products function this way—more light continues in the direction of the beam than in other directions. Other software, such as eQuest, does not allow the option of translucent glazing products. An algorithm to describe the way light actually diffuses from an object is called a Bi-Directional Distribution Scattering Function, though this is not widely integrated into software.

Reverse ray-tracing

Most daylighting engines use the reverse ray-tracing method. This method is logical in that it simulates rays undergoing a user-entered number of bounces and diffusions. However, instead of the rays being emitted from the light source, rays are emitted from the scene viewpoint or sensors themselves and traced backwards until they either reach a light source or the maximum number of bounces. Tracing rays from the scene involves much less computer calculation time than tracing them from each light source, except in limited circumstances. With reverse ray-tracing, a much higher percentage of the rays end up being useful, since rays that are not part of the scene or sensor grid are not calculated. This saves several orders of magnitude in terms of computing time.

While energy simulations are often done at hourly time-steps, daylight and glare simulations are often done at much shorter time-steps (as low as 5 minutes) to ensure glare is adequately considered since the Earth rotates approximately 1° every 4 minutes.

More detail on the inner workings of daylight simulation engines and parameters are discussed in the additional resources listed on p. 120. The Optics6 software from Lawrence Berkeley National Labs references the international glazing database that contains current information on many glazing products worldwide. The software allows specific products to be selected or custom products to be created and then imported for use in Radiance.

When blinds, light pipes, or narrow slots through which daylight is to be simulated are attempted, a more thorough understanding of the software's abstractions and variables is necessary to achieve accurate results.

General guidelines for concept-level daylight simulations are:

- When daylight models are built without wall thickness, the resulting daylight levels should be reduced by 5–10%. When window mullions are not included, a further reduction of 5–10% is necessary.
- The glazing properties should be set based on the solar design strategies given in Chapter 7.
- Skylight glass usually has a lower Tvis than vertical glazing.
- If furniture is not included in the daylit model, light levels may be 30–50% lower, see Case Study 8.3.
- Office enclosures and partition heights can have a significant effect on the success of daylighting.
- The number of bounces should be between 3–6 for concept design, and may be 8 or higher for more detailed studies.
- Details should not be drawn in the daylighting model unless they are critical to the design solution.

CONCLUSION

The best daylight solutions involve a collaboration between the architect, the electric lighting designer, and the controls consultant. Designing for fairly consistent light levels across a room using work plane luminance, minimizing glare using illuminance rendering or daylight glare probability, and thinking about how users will occupy a space are all critical to reducing lighting energy usage.

The case studies that follow illustrate the use and interpretation of most of the metrics discussed. They showcase a variety of projects that have set early goals, used those goals to design spaces, and compared, refined, and validated options using design simulation.

ADDITIONAL RESOURCES

New Buildings Institute, Daylighting Pattern Guide: http://patternguide.advancedbuildings.net/.

Online Radiance reference guide, including technical documents: http://radsite.lbl.gov/radiance/refer/.

Christoph Reinhart's Tutorial on the Use of Daysim Simulations for Sustainable Design is an excellent resource at 100+ pages long.

For extremely detailed daylighting with Radiance, consult Greg Ward and Rob A. Shakespeare (1998) *Rendering with Radiance*.

http://www.ncef.org/rl/daylighting.cfm

http://www.thedaylightsite.com/

For a discussion on glare metrics: http://www.radiance-online.org/community/workshops/2009-boston-ma/Presentations/wienhold_rad_ws_2009_evalglare_intro.pdf.

8.1 DAYLIGHT FACTOR/DAYLIGHT AVAILABILITY

Daylight factor (DF) is a simple metric that is appropriate for climates with predominantly overcast skies. DF calculates the percentage of outdoor light that will reach a given point indoors. It is a single calculation for a space, being neither annual nor point-in-time.

Project type:
Elementary school

Location:
Bainbridge Island, Washington

Design/modeling firm:
Mahlum Architects

Overview

Wilkes Elementary is a new 63,000 ft^2 elementary school on Bainbridge Island in Washington State. The client and project team set goals to reduce energy use and operating costs early in the design phase, along with sustainability goals to meet the Washington Sustainable Schools Protocol (WSSP). Although no specific energy targets were set, the School Board approved the use of technologies such as triple-pane windows, super-insulation using 4″ of continuous exterior insulation, radiant floors and air handlers with heat recovery to improve energy performance and comfort. A ground source heat pump was eventually chosen to provide most of the annual heating and cooling load, with additional peak heating provided by an electric boiler.

Daylighting was an important part of the energy-reduction strategy. It has been linked with improved test scores, so the design team used in-house daylighting expertise to ensure the right amount of daylight would be present. During the schematic design phase, these daylighting simulations were performed to test if the intuitively designed space provided adequate daylight, as well as whether flipping the classrooms to the north of the hallway would improve the daylighting of the space.

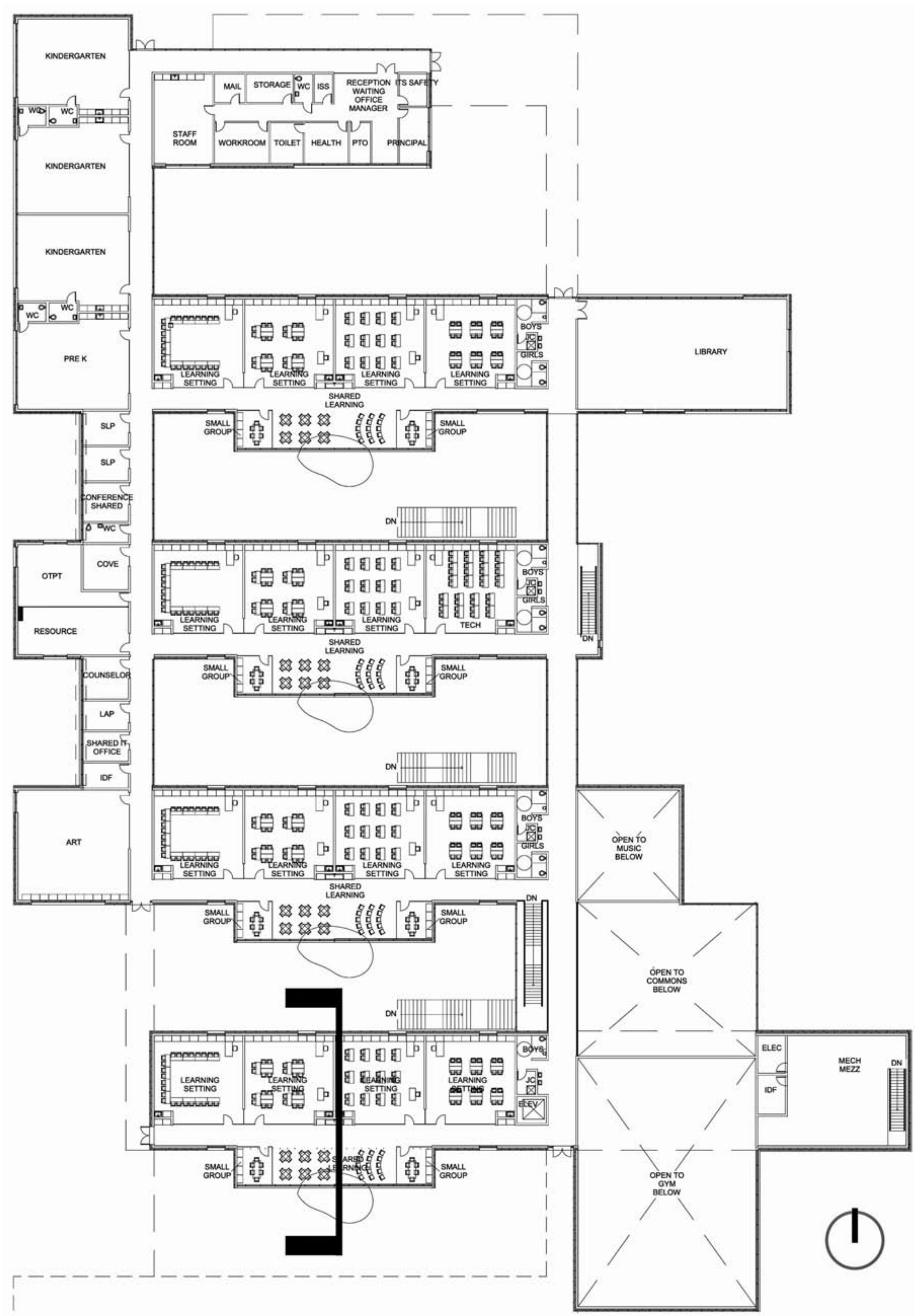
The design for Wilkes Elementary has four classroom bars, which all share the same floor plan and orientation. On one side of a hallway (1) are four enclosed classrooms (2) used for traditional instruction;

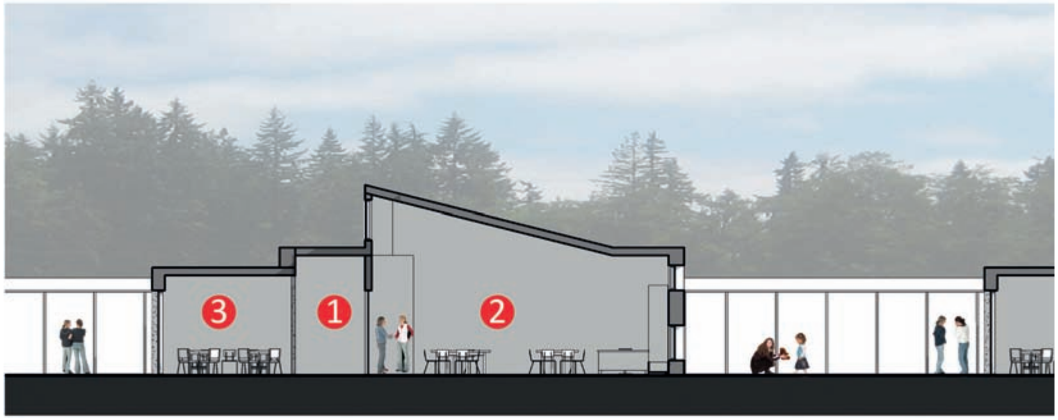
8.16

Rendering looking southwest.

8.17

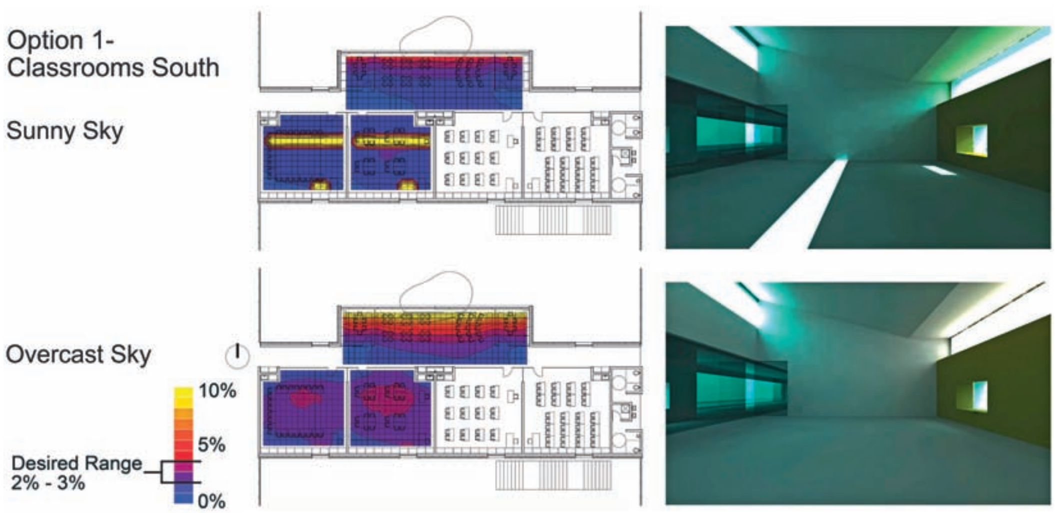
Floor plan.





8.18

Section through classrooms and shared learning space.



8.19

Plan with false color daylight factor overlay, luminance rendering in classroom. Option 1: South.

on the other side are a shared learning space (3) and two small group rooms intended for more flexible learning activities. The classroom bars are separated by learning courtyards, which provide views and outdoor instruction space for each group of classrooms.

Simulation

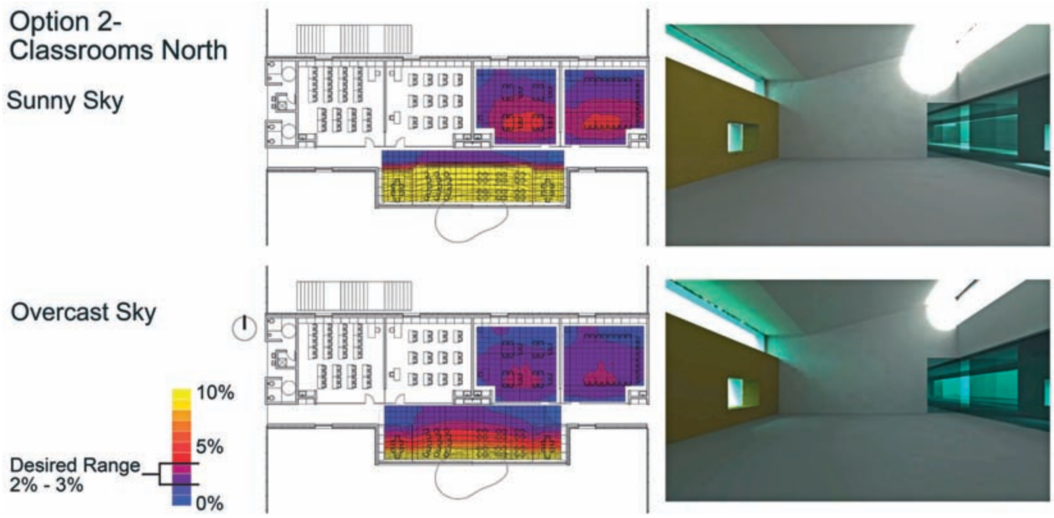
Two options were tested: one that located the shared learning space to the north and the classrooms to the south, with the other testing the classrooms to the north with shared learning space to the south.

The design was tested by importing a simplified SketchUp model into Ecotect for Radiance daylight factor (CIE overcast sky) and daylight availability (CIE Sunny sky) analyses. To capture daylight levels, sensors were located at desk height, 30″ above the floor. Three-dimensional views were rendered as well to look at contrast and glare from daylighting.

Daylight factor and daylight availability in the range of 2–3% were set as a target, a fairly standard range that corresponds to around 20–30 fc indoors when outdoor levels are 1000 fc on an overcast day. Daylight factor also indirectly considers glare, since reflections from outdoor objects are directly related to the outdoor light levels considered in the daylight factor calculations.

Basic material assumptions were used, including high but attainable reflectances for interior surfaces, such as .60 reflectance for walls.

A clear glazing with the conservative Tvis of 50% was chosen to account for the absence of mullions. The final glazing selection used triple-glazing with a Tvis of 61%. While the skylight Tvis was expected to be around this same level, daylight simulations showed that the light distribution would be improved by adding a translucent film that reduced the Tvis to 45%.



8.20

Plan with false color daylight factor overlay, luminance rendering in classroom. Option 2: North.

Interpretation

The results showed that direct sun could not be effectively blocked from the south-facing classrooms. This is apparent in both the luminance rendering and the work plane daylight availability analysis. Even with direct daylight, the classroom falls below the threshold of 2% Daylight Factor. Under overcast skies, however, the classroom performs well, with even light consistently in the 2–3% target range.

With classrooms on the north side, the target of 2–3% is reached for both sunny skies and cloudy skies, with a fairly consistent light distribution in both, successfully reaching the team's goals.

The team agreed that any direct sun would be much more welcome in the shared learning space where students would have more ability to move to avoid glare. The south-facing shared learning was also improved by its adjacency to the sunny side of the learning courtyard, rather than in the shadow that would be cast by a north-facing shared learning space.

The team also revisited the daylighting effectiveness during the design development phase, when structural and mechanical systems were being integrated into the plan and section. Simpler models were used for daylight simulation at this point, since the earlier models had proven the concept.

8.2 DAYLIGHT AUTONOMY: TOP-LIGHTING

Top-lighting can provide the best distribution and quantity of daylight in spaces with adequate ceiling height. However, it can create problems as direct beam sunlight continually moves through a space, creating roving glare problems. Simulating both for daylight autonomy and specific illuminance levels helps the design team navigate between daylight and glare.

Project type:
Single-story library

Location:
Berkeley, California

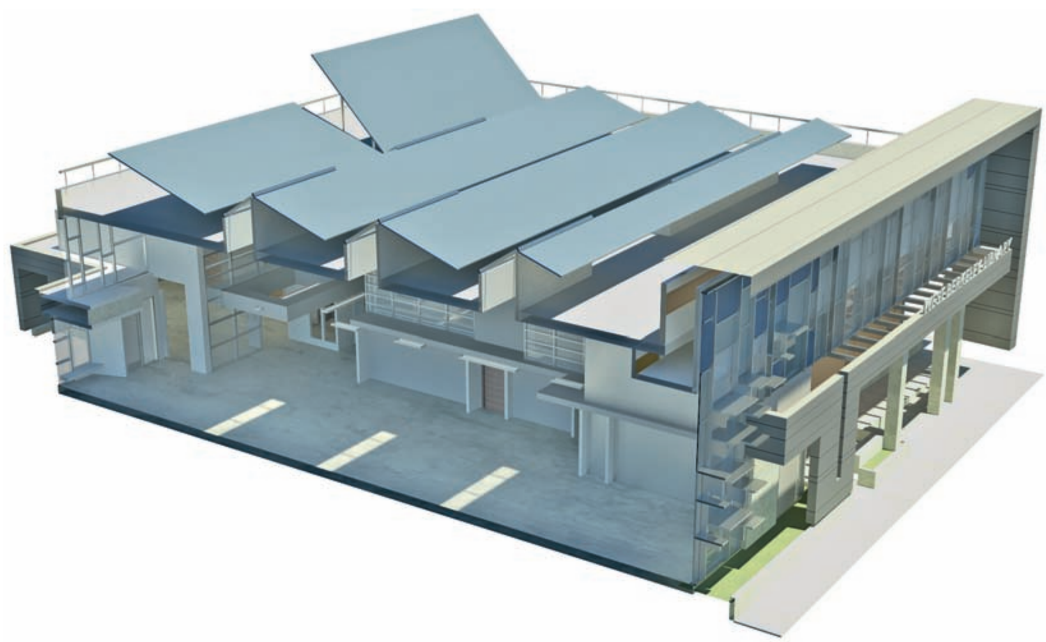
Design/modeling firm:
Harley Ellis Devereaux

Overview

The project team for the 9,400 sq ft West Berkeley Library targeted Net Zero Energy (NZE) during concept design. To achieve this goal, the amount of potential photovoltaic and solar thermal production on the rooftop meant the building could use no more than 15 kBtu/ft^2/year. Low-energy design necessitated daylighting strategies to reduce annual and peak electric lighting use and associated heat.

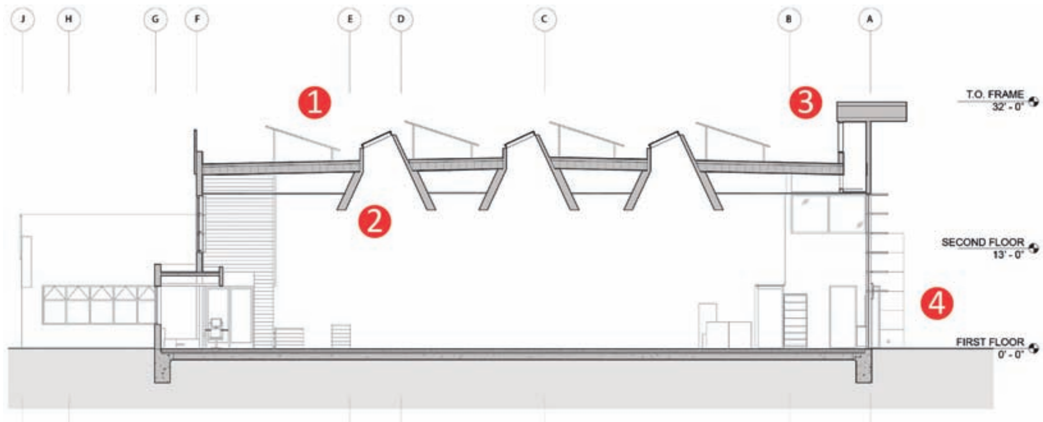
The roof design ingeniously balances the desire for optimally oriented photovoltaic panels (1), skylights for daylighting and ventilation (2), and a wind scoop (3) that allows through ventilation without any ventilation openings facing the noisy street to the south (4).

This daylighting strategy is successful due to the careful roof design with deep skylights that are splayed towards the bottom, which allow for an abundance of ambient interior daylight while blocking most of the sun's direct beam radiation from entering the occupied space. Appropriately, the library's rooftop renewable energy systems are used to absorb the majority of the site's direct beam radiation. During warm periods, the depth of the skylights helps drive the stack effect to provide cooling.



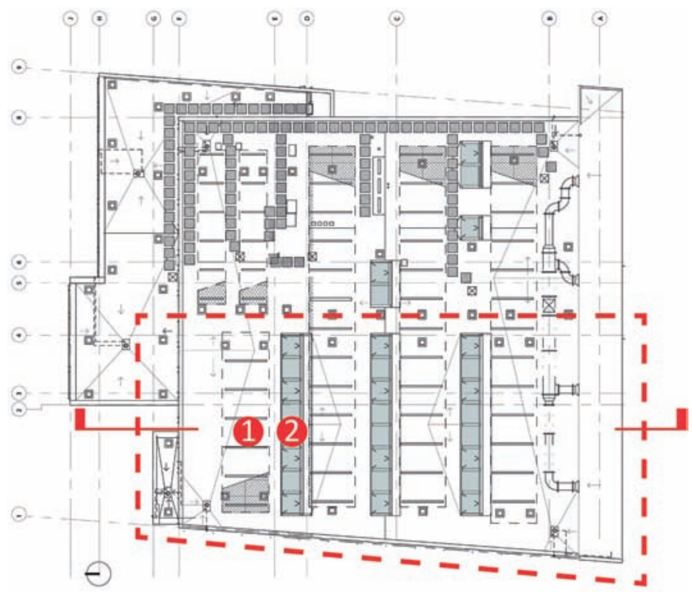
8.21

Rendering looking northwest.



8.22

Building section.



8.23

Roof plan showing skylights and photovoltaics.

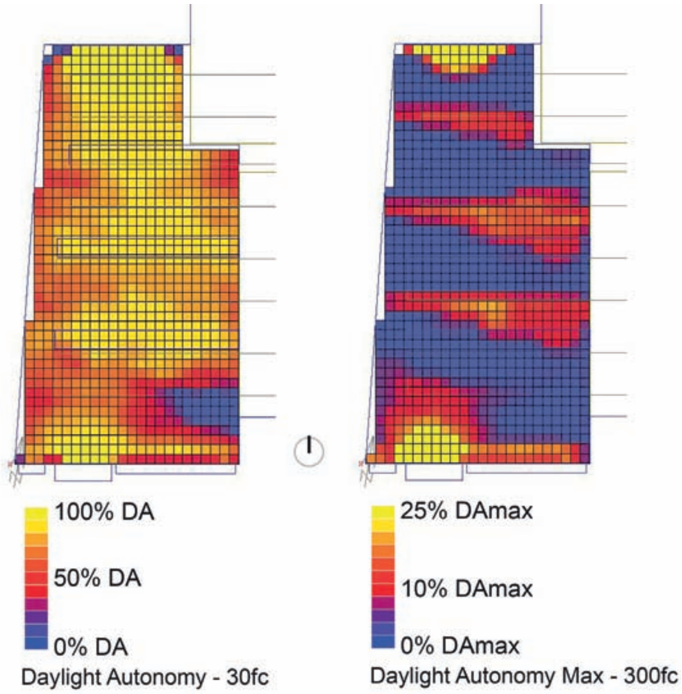
For the skylight and roof design, the team relied on experience and intuition until late in the design process. This was possible since the team had extensive experience with built examples of successful daylighting design and theory, and was able to combine that with rules of thumb to establish the ceiling height and skylight spacing.

While the office spaces can be controlled by employees educated in optimizing building energy use, the public realm of the library requires automatic controls to provide comfort and light for all occupants simultaneously.

Net Zero Energy buildings rely on having the lights off for most of the daylight hours to reduce annual energy use; during peak cooling times this is doubly important as light-generated heat must be removed as well.

Simulation

Daylight Autonomy (DA) measures the percentage of operating hours a given point in space meets a minimum lighting threshold through daylighting. It correlates with times that lights can be dimmed or off, unless glare causes blinds or shades to be drawn, diminishing daylighting levels. Best practices indicated that 30 fc was the target for electric lighting, used as well for the daylight autonomy target.



8.24

Plan view of reading room showing annual DA and DAmax. The skylight geometry is shown to provide enough daylight throughout most of the year with over-lighting in only a few places for only around 10% of occupied hours.

The reading room was designed to achieve 100% daylight autonomy throughout the space using this threshold as a minimum, while minimizing high lighting levels that might cause glare. The daylighting design is so successfully integrated that no overhead lights were installed; the only lights in the main stack area are occupancy and photosensor-controlled LED task lights attached to the stacks themselves.

The simulation was done using Radiance and Daysim software and visualized in Autodesk Ecotect. The daylight autonomy sensor grid was set at 30″ above floor level.

The first Daylight Autonomy study showed areas between the skylights with very low daylight autonomy. A simple fix—splaying the lower portion of the skylight apertures—resulted in these false color diagrams, where the majority of the space achieves close to 100% DA, requiring very little electric lighting use throughout the year.

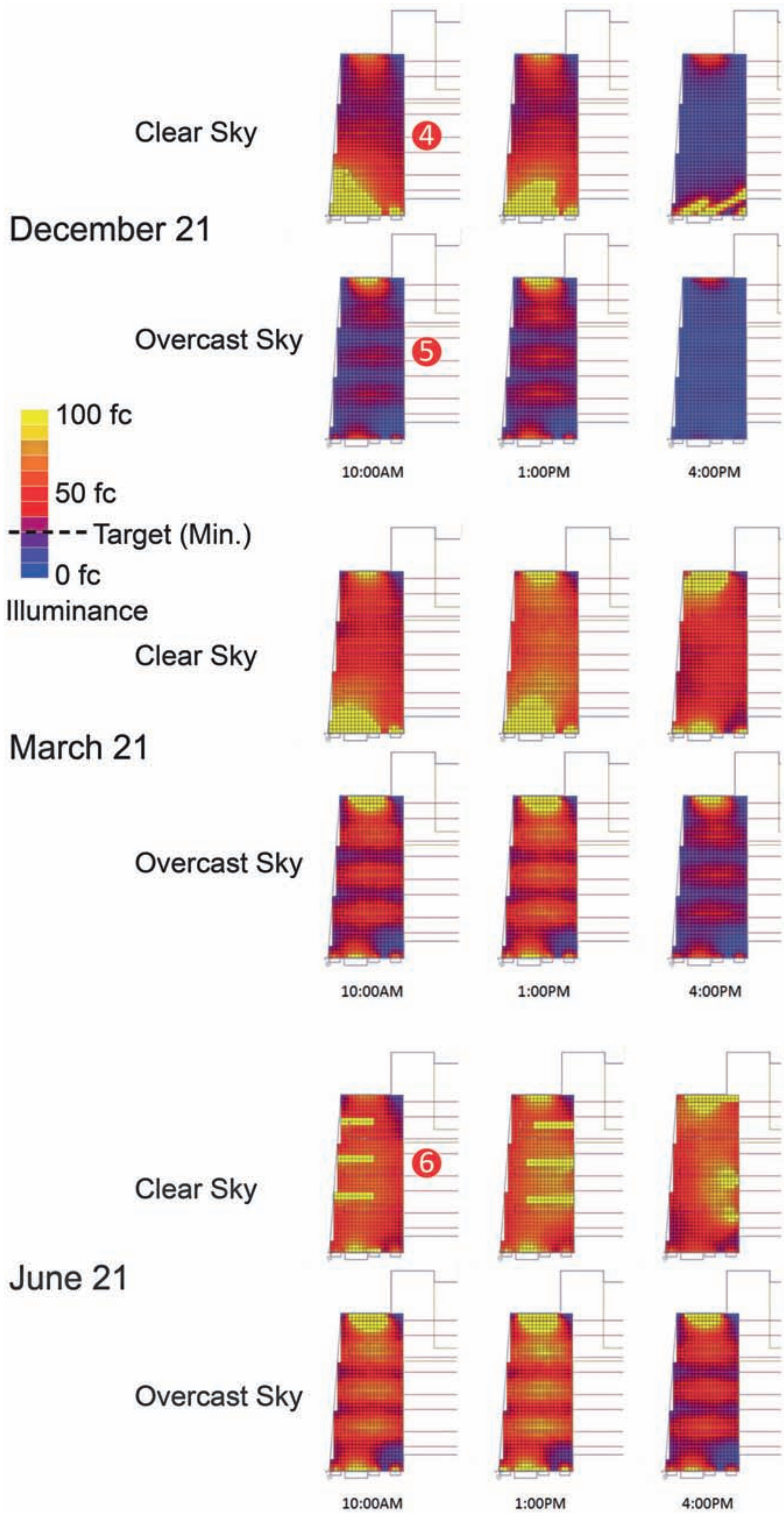
With such a high Daylight Autonomy comes the risk of overlighting and glare. The project team used a metric that predicts overlighting called DAmax, which refers to the percentage of the year where daylight levels exceed a threshold where glare becomes likely. The threshold is often 10x the minimum level, or 300fc for this project. Except for the façades, the entire reading room has a DAmax of less than 10% of the operating hours each year, proving that the geometric design blocked most of the glare potential.

Additional studies show point-in-time (PIT) analyses were run to inform the design team of some of the more typical daylighting scenarios throughout the year. The studies were used to identify potentially problematic areas and to better understand the uniformity of daylighting within the space at specific times, which determine how people visually experience the space.

On the day with the least lighting potential, December 21, both the clear (4) and overcast (5) skies produce illuminance values near the target. The 4 p.m. study is just as the sun is setting, so very little light is available.

March 21 shows good light distribution throughout the day under both clear and overcast skies.

On June 21, when the sun is at its highest altitude, direct light enters the space (6), potentially creating glare and heating up the interior. Automatic shades are deployed during these rare times when direct light is present. Daylight levels are high enough during these times that the small percentage of light that is transmitted through the shades still meet the lighting threshold.



8.25

Illuminance plans, clear sky and overcast sky.

8.3 DAYLIGHT AUTONOMY/USEFUL DAYLIGHT ILLUMINANCE

Daylight Autonomy measures the percentage of occupied time that illuminance levels exceed a specified minimum threshold. UDI is a variation that measures the occupied time between 100 lux and 2000 lux, as well as the percentage of time below and above the thresholds. The upper and lower limits are based on research, but may be changed based on the use of each space.

Project type:
6-story library

Location:
Austin, Texas

Design firms:
Lake Flato/Shepley Bulfinch

Modeling firm:
University of Washington Integrated Design Lab (UW IDL)

Overview

During concept design kick-off for the new Austin Central Library, the team hosted a two-day sustainability workshop with major consultants and stakeholders. At the conclusion of the workshop, broad-based sustainability goals were identified for the library, before form or massing had been given to the building.

The team set a goal to provide daylight and views from 75% of regularly occupied spaces. Early concept design began with a program matrix identifying which spaces should be most associated with daylight and views, as well as massing studies centered on splitting the building footprint in two with a daylit atrium.

The simulations in this case study helped determine the lighting power savings due to successful daylighting strategies used throughout the design process.

Simulation

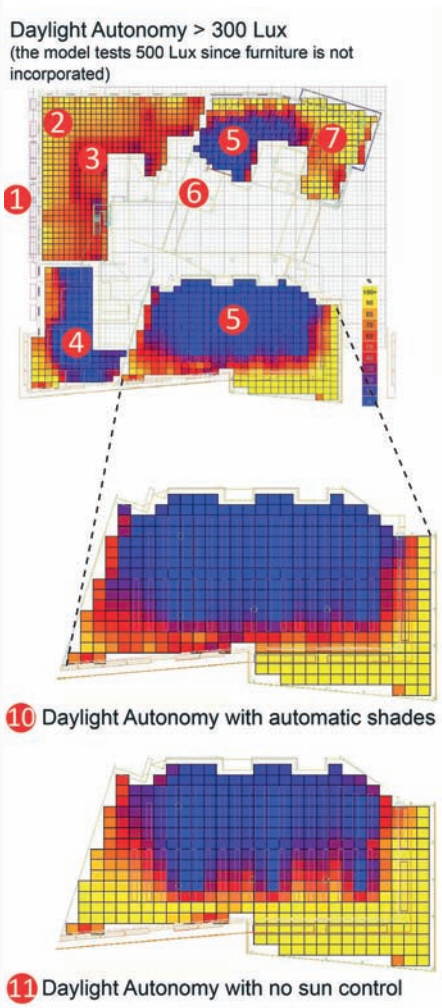
A schematic-level Revit model was exported to Ecotect, where materials were assigned reflectances (walls =.50; ceilings=.80; and exterior ground = .08). Windows were assigned a visible transmittance of Tvis= .63 and skylight Tvis= .40. The 4th floor was simulated since it is representative of the other

8.26

Rendering looking northwest.

8.27

4th Floor Plan.



8.28

DA study on 4th Floor Plan, with enlarged areas showing sun control studies.

floors and mid-height. Exterior shades (1) on the West side of the Library were included as 50% opacity mesh screens, reducing glare and available light.

Within the model, a grid of sensors was located 30″ above floor level to measure daylight levels. The geometry was exported from Ecotect to Daysim for annual daylighting calculations.

Since simulations were done early in design, furniture such as seating and tables were not built into the daylighting model. While the target for interior lighting was set at 300 Lux, the daylight autonomy threshold was set to 500 Lux to account for the omitted furniture. The UW IDL's experience with simulation and validation suggested that this factor of 40% (500 Lux instead of 300 Lux) would reasonably predict daylight autonomy as if the simulation had included furniture.

A schedule for the daylight autonomy simulation assumed the office would be occupied from 8 a.m.–6 p.m. and public spaces would be used from 10 a.m.–7 p.m. Within Daysim, automatic 75% opacity roller shades were programmed to be deployed when solar irradiation exceeded 50W/m^2 and retracted when direct sun was no longer present. The Daysim outputs were imported back into Ecotect's analysis grid for visualization.

Useful daylight illuminance (UDI) is calculated within Daysim as well. UDImax, which was chosen in this simulation to return the percentage of occupied time that a sensor received more than 2500 Lux, identified spaces where occupants would be more likely to experience discomfort glare.

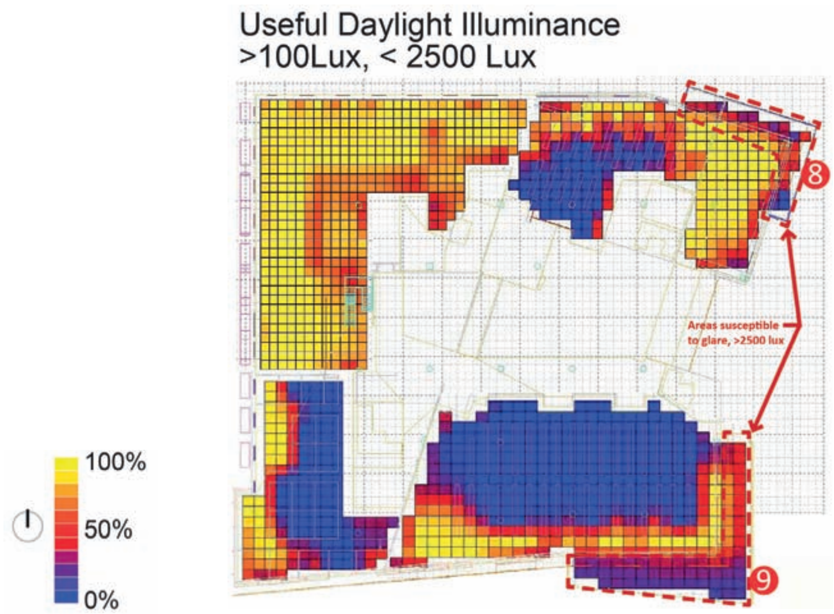
Interior core spaces that did not achieve daylight autonomy above the threshold were treated with different ceiling material so as to visually disconnect the space from the daylit perimeter areas. Since part of the library uses dimming lights and other parts are electrically illuminated, lighting controls are critical to comfortably transition from one space to another.

Interpretation

The open office area (2) on the northwest corner receives very good annual daylight levels due to orientation, screening, and light from two sides. Enclosed offices with glazed walls (3) were located towards the interior so that they could still receive daylight, and opaque-walled private offices (4) were located on the southwest where glare would require individual control.

Areas with book or periodical stacks (5) are difficult to daylight in multi-story libraries due to their close spacing. Although they were not tested separately, minimum light levels in elevator lobbies and other vertical circulation areas (6) generally have lower requirements (100–200 Lux) than in reading areas.

The reading room (7) achieves a daylight autonomy near 100% throughout. The UDI study shows that glare may be a problem near the northeast windows (8) due to



8.29

UDI Study.

8.30

Radiance illuminance rendering of a section through the Ecotect daylight model.

illuminance levels over 2500 Lux. Since people are free to move around the space and orient away from any glare, however, a variety of light levels can actually be an amenity. Further, since this space faces east and the library is expected to open at 10 a.m., direct sun glare in certain portions would not occur beyond the first hour or two of operation.

The outdoor, covered reading porch (9) shows areas that are often over 2500 Lux as well, though this space is even more flexible than the reading rooms above.

The south-facing book stack area was tested for daylight autonomy with (10) and without (11) automatic shades. While daylight penetrates further into the space with no automatic shading, most of this light will be direct light which may cause glare and overheating of the space. The option of manual shades was also considered; however, this would probably result in blinds being drawn in the morning, blocking light all day and requiring more electric lighting.

Lights within the atrium were installed to maintain minimum light levels at night. During the day, these areas are successfully daylit, so the lights are on continuous dimming with photosensors, and they completely turn off when target daylight levels are reached.

Lights in the office area were also dimmable, with task lights provided for each desk so the lights may be dimmed or turned off even when light levels are below 300 Lux.

Additional Studies

Each space type was simulated individually as well to test for effectiveness of additional shading, screening, and blind automation.

Case study 8.4 illustrates a physical model simulation of the atrium space.

8.4 PHYSICAL DAYLIGHTING: LUMINANCE

Physical daylighting models can be "explored" and qualitative experiences of space perceived more easily. Unlike digital simulations, physical models offer real-time feedback, as the eye or a camera can be moved throughout the space easily. High dynamic range (HDR) photography can capture luminance metrics for later analysis, with the results being similar to digital simulations. The results can be more accurate as daylight is perfectly scalable, and abstractions within daylighting software trade speed for accuracy.

Project type:
6-story Library

Location:
Austin, Texas

Design firms:
Lake Flato/Shepley Bulfinch

Modeling firm:
University of Washington Integrated Design Lab (UW IDL)

Overview

After setting a goal of being the best daylit library in the United States, the project team for the Austin Central Library simulated daylighting through computer and physical analyses throughout the design process. An early design move carved an atrium through the center of the project. Skylights above the atrium were designed to achieve balanced daylight through all sun positions. During schematic design, different strategies for roof monitors were tested to bring daylight deep into the atrium.

In the design development phase, the atrium was studied during a focused, two-day workshop with the architects, interior architects, daylight consultant, and electric lighting consultant. A large-scale physical model of the atrium was built and tested outdoors as well as modeled in the computer. Iterations of different roof forms and glazing materials were tested. The resulting design incorporates a light-filled atrium that uses saw-tooth roof monitors with vision glass and a central, translucent skylight that plays diffuse light throughout the atrium.

While achieving work plane daylighting metrics is crucial to reduce energy use, a high quality balance of light is equally important. The design team worked with the UW IDL in early design, exchanging

8.31

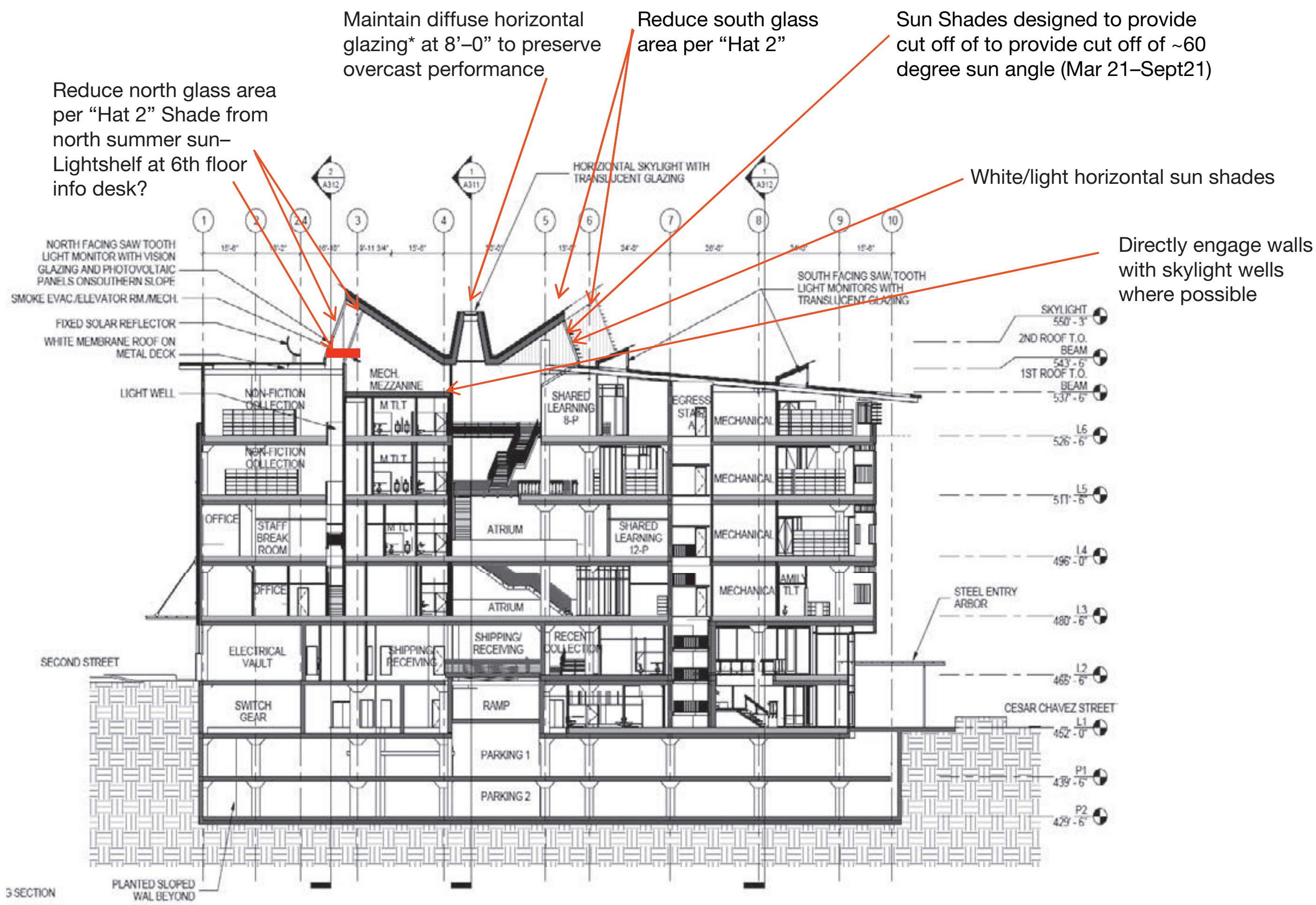
Rendering looking southeast.

8.32

Model as designed, Day One (Left). Reduced southern clerestory, Day Two (Right).

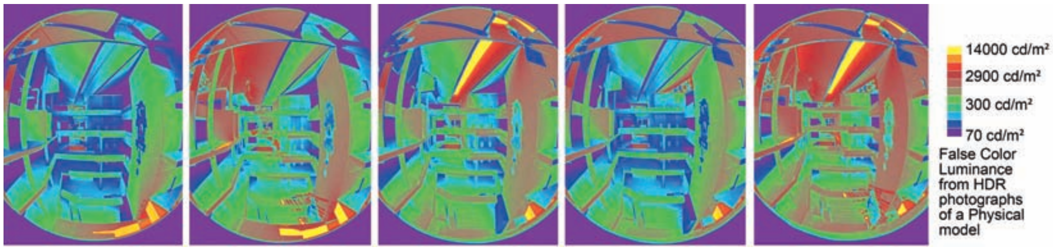
8.33

Follow-up design recommendations from the UW IDL based on the two-day daylighting effort.



Atrium Recommendations: East Glazing and Entry Approach

*Quantify cooling load impacts with energy model



8.34

From left to right: Sidelighting Only, South Clerestory Only, Translucent Skylight Only, North-Facing Skylight Only, All Openings uncovered.

photos of libraries with high-quality daylighting, conceptual SketchUp models that allowed the UW IDL to provide feedback on floor-to-floor heights, plate depths, and implications of various design options.

Simulation

Lake Flato built a 1/4″–1′0″ physical model of the central atrium to test daylighting and spatial qualities early in the design development phase. The model was constructed of foam core covered with paper, felt, and wood as needed to represent the colors and brightness of the finish materials. Even an art piece that was expected to absorb light was created out of green paper.

In March of 2012, Lake Flato, Shepley Bulfinch, Clanton and Associates (electric lighting design), and the UW IDL gathered in San Antonio's Travis Park to test the physical model during sunny conditions.

The physical model allowed the team to gather around, inspect, and instantly compare options on the model.

Interpretation

One very informative study involved covering the entire model in a black cloth and letting sunlight and diffuse daylight into just one aperture at a time to see each aperture's contribution. A fish-eye lens was used to produce a series of false color HDR images that show the individual contribution of: side-lighting, south clerestory, horizontal translucent skylight, and north-facing clerestory. The fifth image shows all openings uncovered.

The team realized that the translucent skylight was contributing the majority of light to the atrium, since the 'Translucent Skylight Only' image looks similar to the image with all the openings uncovered.

The composite image also shows a very good balance of light within the space. Most of the vertical surfaces within the atrium, including the translucent slot, are shades of red, meaning they are very similar in terms of perceived brightness (luminance). The greenish areas have a contrast with the red areas of less than 10x luminance, so there is little chance of glare. Since this design was tested under the most demanding conditions (sunny skies), the balance is even more commendable.

Achieving this quality and balance of light under sunny skies (the most glare-prone conditions) required many design iterations and experience.

Since the electric lighting designer was at the daylighting session, the project team could exchange ideas about electric lighting for both daytime and night-time scenes. While the atrium was well daylit, the model showed areas where electric lighting would be useful to complete the balance.

On the second day of testing, the team looked at options based on the experiences from the day before. One involved adjusting the southern clerestory to be recessed further (6), reducing the area of glazing and providing more shading, thus reducing heat gain. This move was shown not to significantly reduce light levels or adversely affect the balance of the space.

While the design continued to evolve after these studies, the designers' experiences with real-time daylighting simulation informed future design moves, perhaps the most valuable lesson. Jonathan Smith of Lake Flato commented that the charette "was hugely helpful from both a spatial and lighting perspective, since we were able to test a lot of our assumptions about the architecture."

Additional Studies

The UW IDL prepared a series of follow-up recommendations for the design team using a series of diagrams. One example illustrated a refinement of the south clerestory to reduce glazing area and reduce direct sun in the shared learning space.

Other recommendations included creating increased transparency and the perception of brightness as one enters the atrium by creating a slightly darker "transitional space" through which visitors enter the space.

A further study included eliminating the potential for direct sun at the circulation and information desks, since this is one of the most common sources of visual comfort complaints within libraries. The employee cannot choose to move or look in another direction at a fixed counter, so any glare will cause discomfort.

One recommendation to address this was the reduction of north-facing glass and the inclusion of targeted internal sun-control at the 6th floor information desk, to block glare from high sun angles.

8.5 3D ILLUMINANCE ANALYSIS

A daylight Illuminance Rendering shows the light falling on each surface. An analysis using Radiance allows the user to click on any point in a rendering to see a specific illuminance value. The illuminance values are displayed qualitatively, allowing a reading of the space to determine hot spots and potential glare. Each analysis is done for a specific day, time, and sky condition.

Project type:
3-story enclosed mall

Location:
Wuxi, Jiangsu, China

Design/modeling firm:
Callison

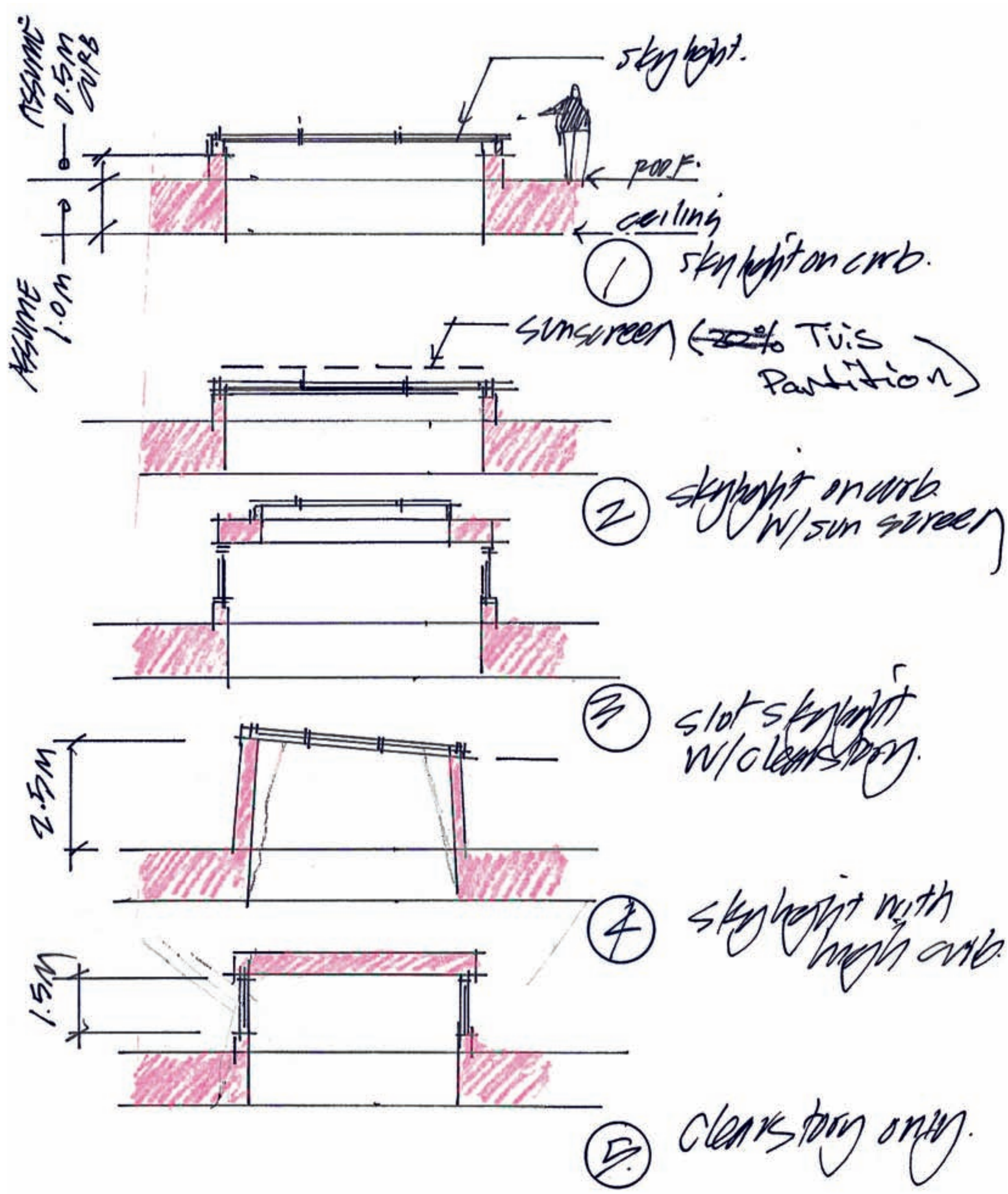
Overview

Retail environments require very controlled daylighting, since it is meant to enhance, but not compete with, the retailers' interiors. In early concept design, the project team looked at providing a controlled, daylit atrium with a series of skylight apertures. The project team explored several options, testing five skylight options initially, to determine the ideal geometry for the skylights.

Over 100 simulations were run through Radiance, in three phases. Options 1 and 5 from the first phase are shown in this example. The goal was to allow some sky view, but control daylight to brighten vertical surfaces, except the vertical surfaces at the retail store fronts. The simulation team was interested in the distribution of light in four different areas described below.

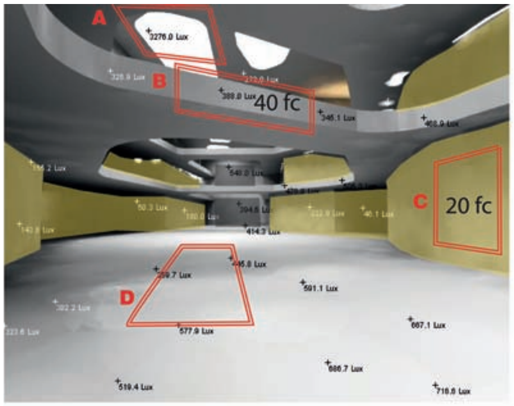
These simulations broadened the discussion of skylight design to include simulated performance characteristics based on geometry and glazing location. The client was able to verify whether each design

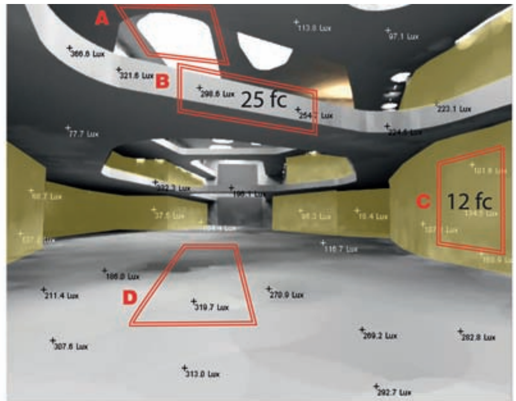
8.35
Rendering.

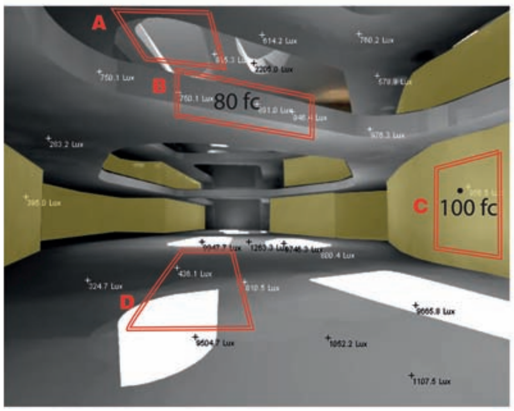


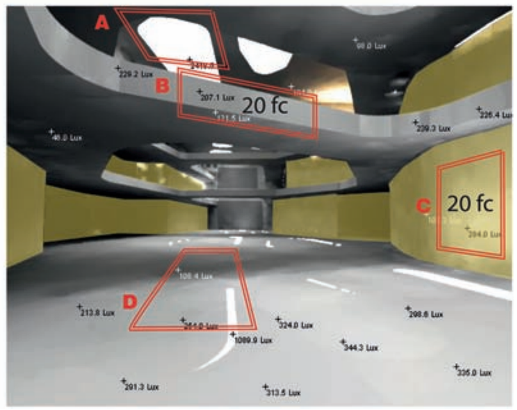
8.36

Sketches of the five skylight options.









8.37

Skylight Option 1, Winter, Partly Cloudy Sky.

8.38

Skylight Option 5, Winter, Partly Cloudy Sky.

8.39

Skylight Option 1, Summer, Sunny Sky.

8.40

Skylight Option 5, Summer, Sunny Sky.

provided enough daylight and compare the performance of the five early options. Later in the process the same type of simulation allowed the interior designers to sculpt daylight delivery strategies more intelligently.

Simulation

Geometry was built in SketchUp and imported into Ecotect, where opaque surfaces were set to .56 reflectance and all glazing was set to a Tvis of 50%. Radiance was used to generate these images, which were altered to include a yellow highlight over the storefronts for client presentations. Winter conditions were simulated for December 3rd at noon with an intermediate sky. Summer conditions were simulated on July 3rd at noon, with a clear sky. The number of ambient bounces was set to four to achieve an accuracy appropriate for conceptual design. Ecotect with Radiance export allows multiple simulations to run simultaneously as long as the rendering filenames are unique. While each camera view may take 5 minutes, 20 views can be completed in 30 minutes of run-time on a good computer.

Four cameras were set up in the model, and each was run through dozens of time and date rendering simulations to determine overall design.

This model was done during concept design for purposes of general light distribution, so it does not include detailed material selection or furniture, which was accounted for in later simulation phases.

Interpretation

Although nearly 100 simulations were run, an analysis of these four illustrate the use of illuminance images for comparing design options.

A *Skylight aperture*: The skylight itself can produce glare if the aperture appears too bright next to the adjacent ceiling surfaces. While the aperture should reflect light down to the space below, direct beam light visible on the skylight itself from below can be a nuisance. All of these early studies have too much contrast between the skylight and the adjacent ceiling. Later designs for this space softened the transition between the skylight and the ceiling, reducing glare potential.

B *Vertical surfaces*: Occupants generally judge a space's brightness based on vertical surfaces. A good range for the vertical surface highlighted is 20–100 fc throughout the year. This study measures illuminance, so the material quality of the walkways will modify the apparent brightness. Retail malls usually use an off-white on these surfaces to maximize apparent brightness.

C *Retail storefronts*: While these are also vertical surfaces, the retail storefronts are generally used for signage and display. Retailers like to control the quantity and quality of light on displays, which will get washed out if daylight is excessive. A moderate light level in this area will allow the light at the back of the store to draw the eye into the store. A consistent light level above 30 fc will motivate the retailer to increase light levels within the store, favoring option 5 over option 1 during Summer months. Both perform reasonably under partly cloudy conditions.

D *Floor*: A retail atria floor can be enhanced with some direct beam light, but large patches of daylight create glare and discomfort. Shoppers and kiosk employees who are in the direct beam light will experience glare and may feel too warm regardless of ambient air temperature. Option 1 (Summer) shows a large, continuous direct daylit area, which is not desirable in most climates. Option 5 (Summer) has smaller, discontinuous patches of direct daylight, which provides a desirable sparkle or highlight to the floor area. Adding high density frits on Option 1 would help somewhat mitigate the ground-plane heat and glare issue.

Additional Studies

The second phase of simulations blended the designs of options 3 and 4 at the client's request, with similar objectives as this study. The third phase analyzed for the specific quantity and quality of daylight along the mall and in the main atrium, using specific structure and interior design concepts, as well as false color rendering views.

Solar irradiance studies were also performed on the glazed portion of each skylight configuration to compare the potential for heat gain.

8.6 SKY CONDITION FROM HDR PHOTOGRAPHY

HDR photographs are accurate maps of luminance quantities. Instead of using a generic sky for daylighting, HDR photographs can be used to create a site-specific sky with contextual lighting. They can also be used to simulate accurate luminance-based views from within a space, even when shades or blinds are used.

Project type:
Museum of History and Industry

Location:
Seattle, Washington

Design/modeling firm:
LMN Architects

Overview

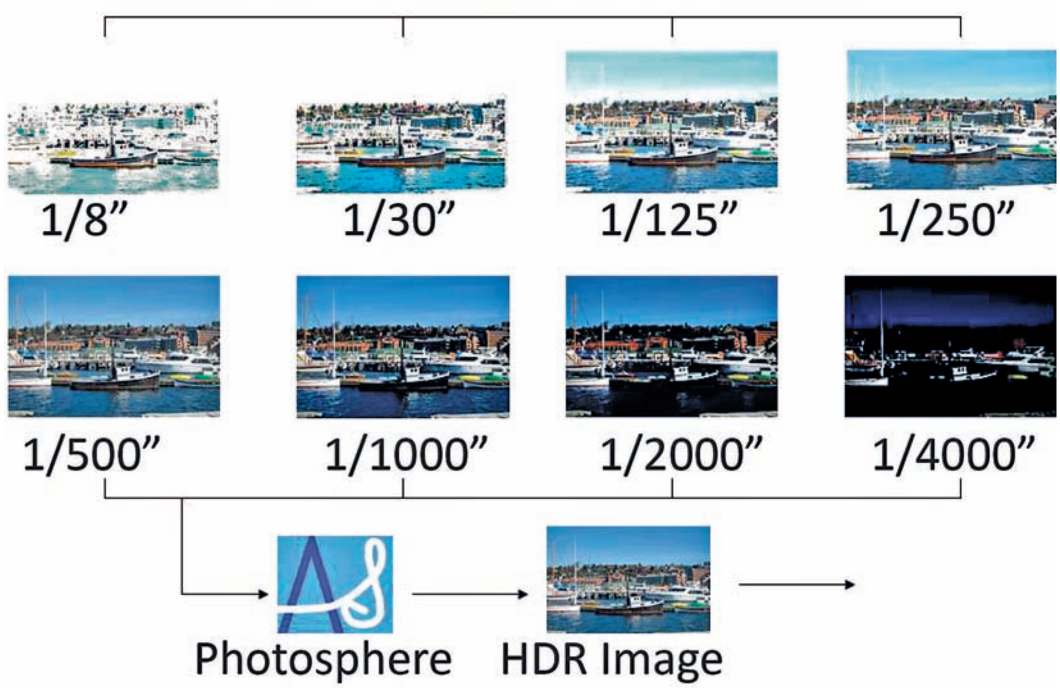
The Museum of History and Industry (MOHAI) was relocated in 2012 to the historic Armory building at the southern tip of Seattle's Lake Union. The existing building has regularly spaced windows around the exterior and a large day-lit drill hall in the center. There are great views in all directions, but with those views come concerns about visual comfort and excessive exposure of museum exhibits to ultraviolet rays. An emerging way of simulating these conditions is the use of High Dynamic Range (HDR) photography.

LMN Architects used a series of HDR photographs taken from the rooftop of the Armory building to record the surrounding environment. The HDR image was remapped from a flat plane to a sphere and then the digital model of the building placed within this HDR sky dome. A series of daylight renderings from the interior of the building were created using Radiance.

8.41

Photograph looking east.

Source: Courtesy of LMN Architects.



8.42

HDR image assembly.

Source: Courtesy of LMN Architects.

A single photograph is not capable of representing the same range of light our eyes can see, but the camera's performance will improve if multiple images of different exposures are merged. Some of those pictures capture the detail at the dark end of the spectrum while other images record the brightest. These images can be digitally merged and the new HDR composite image can be calibrated against a light meter reading taken at the time of the photographs. The general process of mapping luminance levels with HDR photography is described in "Evaluation of High Dynamic Range Photography as a Luminance Mapping Technique" by Mehlika Inanici and Jim Galvin.

Daylight studies with Radiance will typically use a CIE or Perez sky which is a mathematical model of light distribution for sky conditions such as clear sky, cloudy, overcast, and more. These sky models are a great starting point for simulations but they do not contain any of the surrounding topography, buildings, and other obstructions that will create reflections and a building's access to light, meaning that those objects would need to be digitally modeled to understand their effects.

HDR photographs simplify the process of capturing the surrounding environment and can then be used as a replacement for generic sky models. Since each set of HDR photographs only represents a single day and time, this method is limited in its usefulness for running simulations under a wide range of lighting conditions. For this project, it was important to have the surrounding environment as part of the simulations to visualize the views from within the galleries.

Simulation

To create the HDR sky, a Canon EOS 5D Camera on a tripod captured a series of images in all directions. Each series included 12 shutter speeds (1): 1/2", 1/8", 1/15", 1/30", 1/60", 1/125", 1/250", 1/500", 1/1000", 1/2000", 1/4000", and 1/8000", with f-stop constant at 5.6. The images were taken on a sunny March day around noon, and then composited within Photosphere, a software that creates HDR images. It was then saved as a sky condition map for use in the Radiance simulations.

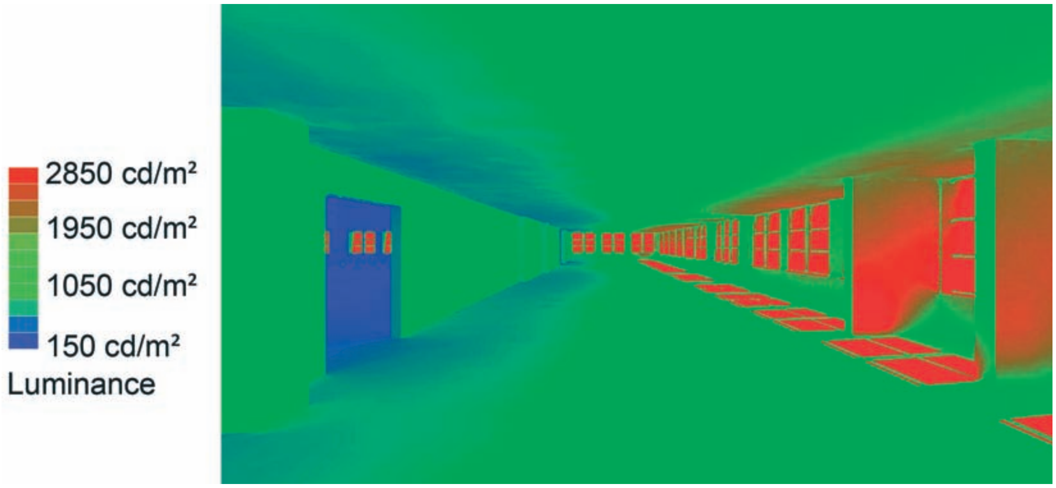
A 3D luminance simulation looking northwest was run using the HDR sky, also called a light probe. The study was able to capture the views that would be seen out of each space while also simulating the quality of daylight that would be available on a clear day.

A challenge in using the HDR sky is that shadows are not as crisp as with the CIE skies. This is due to the extreme brightness of the unobstructed sun; while the rest of the sky is adequately mapped for

8.43

Luminance rendering looking northwest.

Source: Courtesy of LMN Architects.



8.44

False color luminance rendering along west façade.

Source: Courtesy of LMN Architects.

luminance by HDR photography, the sun is too bright to be captured, meaning that additional means need to be employed to adjust for this by locating point light source within the Radiance model at the sun's location.

A false color luminance image along the west façade uses this method to determine luminance levels within the space. Other than the direct sunlight, the space provides a very even lighting level, mostly between 350–750 cd/m^2, a 1:2 range.

Since the Museum had maximum illuminance levels that could fall on objects and artifacts, interior shade systems were necessary. The shades would be deployed automatically when direct sun was on each façade.

Ideally the shades would block unnecessary light to stay within the Museum's constraints, but be open enough to maintain views of Lake Union and Downtown Seattle. A luminance rendering compared fabric shades to test indoor light levels and views, including a darker shade and a white shade.

There were a number of studies looking at how different shade fabrics would affect the overall light distribution in combination with visualizing how the color and opacity of the fabric affected the visual perception of the historical windows. The darker shades were eventually chosen since they allowed views while blocking direct sunlight.

8.45

Luminance rendering looking northeast.

Source: Courtesy of LMN Architects.

8.46

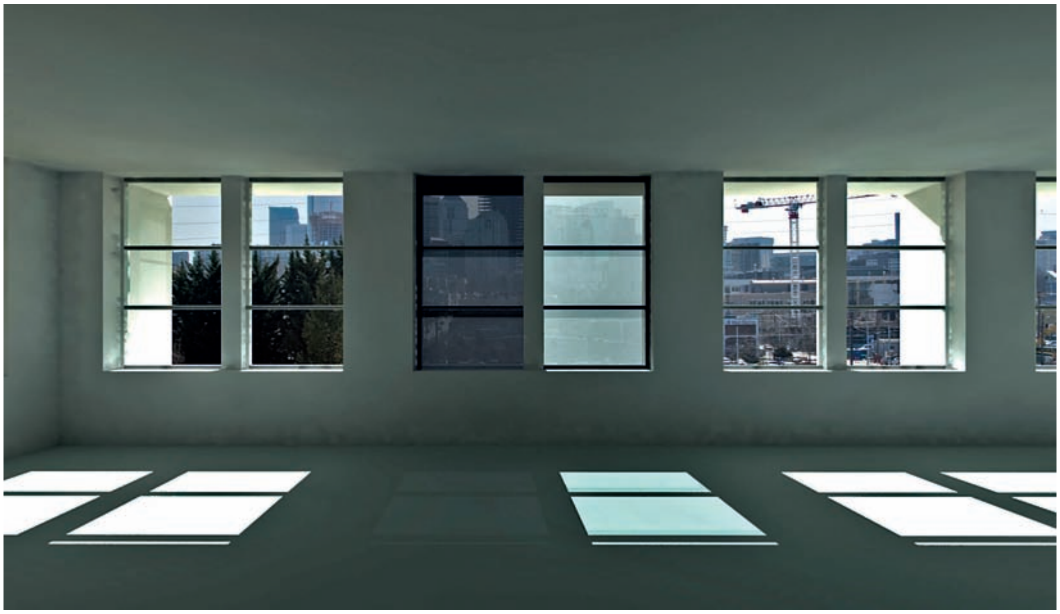
Luminance rendering looking south, testing two shading options.

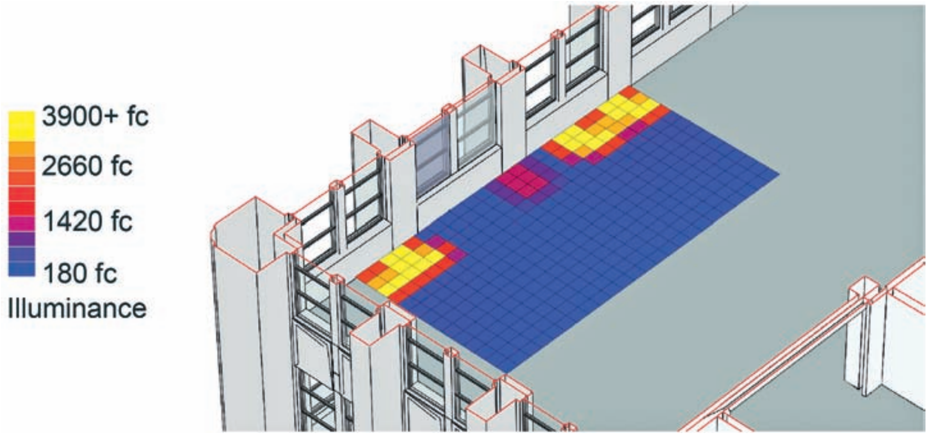
Source: Courtesy of LMN Architects.

8.47

Autodesk Ecotect false color illuminance map showing two shading options.

Source: Courtesy of LMN Architects.





Since the HDR sky contains actual luminance data from the surrounding buildings, the Radiance rendering was used to predict the quality of the view through the shades much more accurately than other methods, such as simply relying on the shades' opacity. Further, the Radiance renderings were shown to be consistent with measured and experiential testing on site within the existing building. This allowed the design team to calibrate and validate their results during the design process and increased the design team's confidence in the simulations.

A work plane illuminance analysis allowed a quantitative output in footcandles with the fabric shades used, on the basis of which the Museum exhibit designers could make decisions. The illuminance testing was most relevant to considering where—and where not—to place light-sensitive documents.

Other studies that were performed on MOHAI included LEED daylighting analysis which allowed the daylighting and views credits to help qualify for LEED Platinum certification.

8.7 DAYLIGHT GLARE PROBABILITY

Project type:
2-story lab. 87,000 ft^2

Location:
Great Lakes Region, USA

Design/modeling firm:
Skidmore, Owings & Merrill, Chicago

Daylight Glare Probability (DGP) conveys the likelihood of glare from a specific viewpoint at a specific time of day. The output from Evalglare software is a single number that describes the potential for glare within a scene. It can be useful when comparing daylighting scenarios to determine the one least likely to cause eye discomfort. Evalglare also maps color onto a view to show the locations of potential glare sources.

Overview

Roche Pharmaceuticals required that critical program areas be daylit for aesthetics, performance and health in their new, 2-story lab building. The design team proposed a top-lit atrium in the concept phase that would allow views and daylight through the entire cross-section of the building. The design progressed as numerous roof apertures were evaluated for point-in-time illuminance and visual comfort.

Simulation

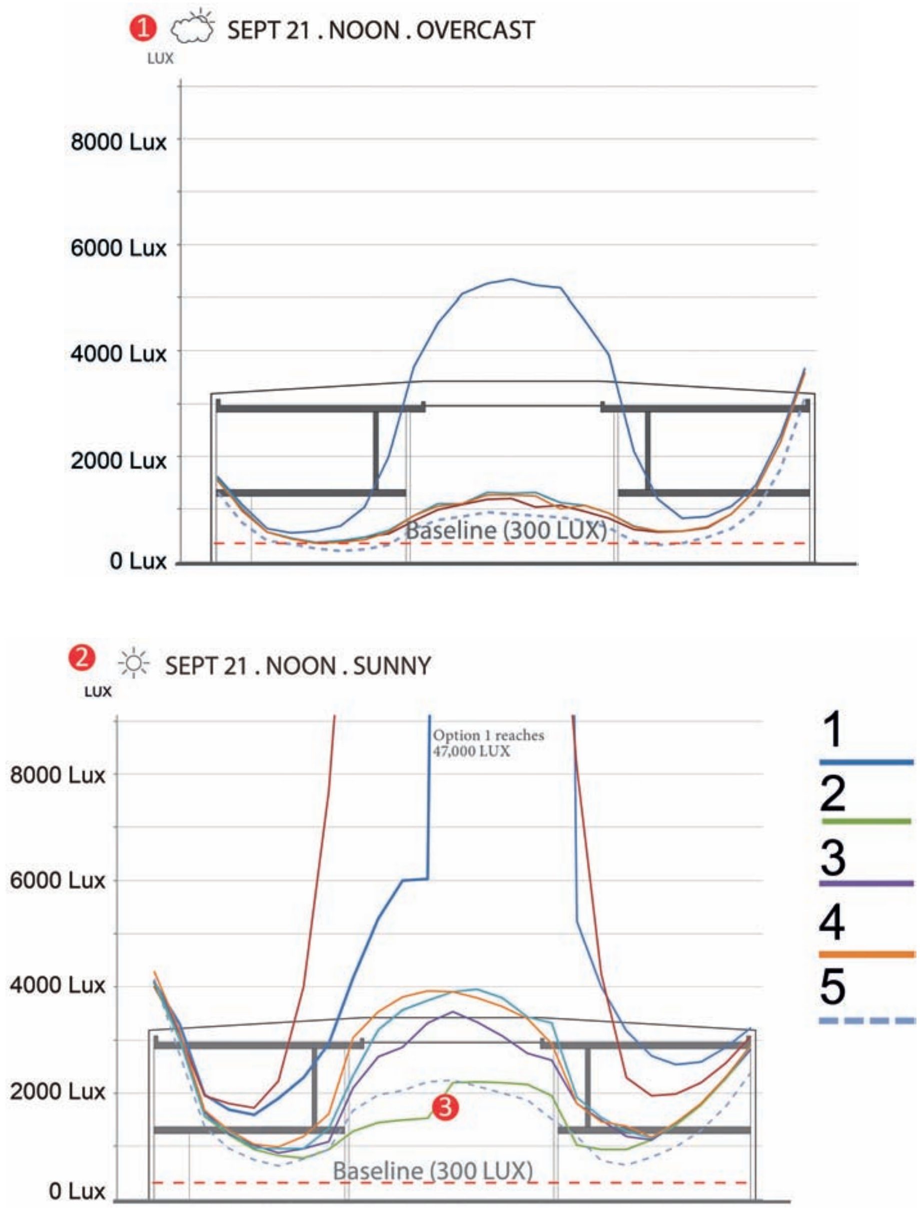
During the schematic design phase, a Revit-based design model was imported into Ecotect and rebuilt to contain several skylighting options. Many other options were simulated to find the right balance of daylight with minimal glare.

These studies used some custom materials that were created in Optics 6, such as cloth and translucent skylights. The material definitions were then inserted into the advanced export features of Ecotect before exporting to Radiance.

8.48

Rendering looking south from the second floor.

Courtesy of Skidmore, Owings & Merrill, Chicago.



8.49 and 8.50

Atrium sections showing daylight levels in overcast and sunny conditions.

Courtesy of Skidmore, Owings & Merrill, Chicago.

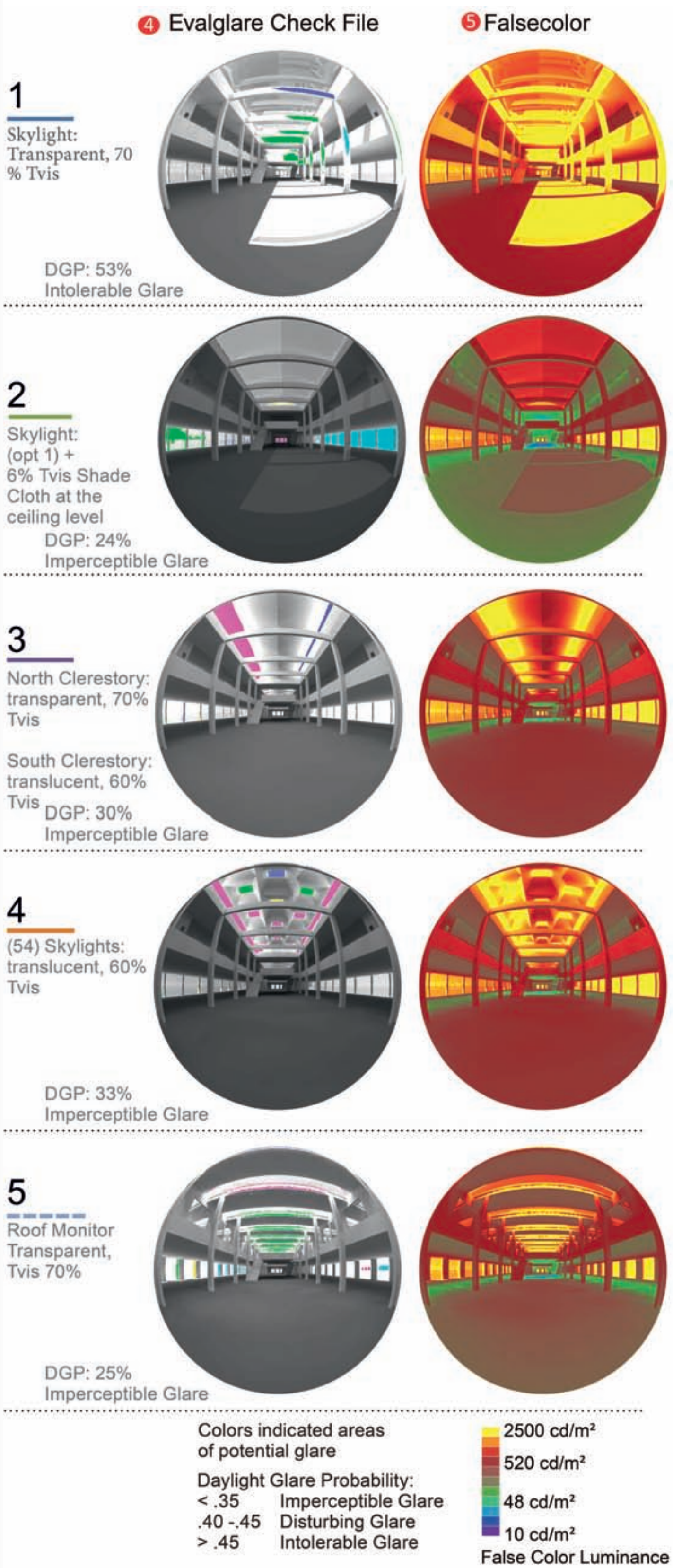
Reflectances were set as: ceiling = 80%, wall = 50%, floor = 20%, and illuminance sensors were placed 30″ above the floor.

Illuminance data from each image was imported into Excel and graphed to show daylight levels of the various options through a typical section through the building, under both overcast (1) and sunny skies (2). The baseline of 300 Lux is shown dashed.

Except for Option 1, all designs have very similar daylight contours through the section with overcast skies.

Under sunny skies, however, option 1 overlights the space. Option 2 uses similar geometry to option 1, but eliminates direct sunlight by incorporating fabric below the skylights. Options 2 and 5 provide the most consistent light levels (3) at the work plane. The other options all provide around 3500 Lux at the center of the high-bay space.

Since all options supply at least the minimum light level necessary throughout the section, options that reduce glare and provide a more consistent light level throughout the space were preferred.



8.51

Evalglare images tonemapped and scaled with false colors.

Courtesy of Skidmore, Ownings & Merrill, Chicago.

Southwest-facing luminance renderings were created with Radiance as 180° angular fisheye views to process for DGP data and check files in Evalglare software (4). Evalglare assigns colors to potential glare sources so they can be identified; in this case the default was used where areas at least five times brighter than the average luminance are colored.

These same base images were also tonemapped and scaled with false colors in Photosphere (5) to show specific luminance levels.

Interpretation

Balancing daylight levels across the section depth with high visual comfort was critical to selecting top-lighting strategies. Aesthetics and solar loads were also key drivers.

Option 1 overlit the space with direct daylight under sunny conditions, resulting in a DGP of 53%, which is considered intolerable glare.

Option 2 proposed a deployable shade cloth to mitigate direct sun from option 1. While this strategy was successful in terms of daylighting, it was ruled out due to the energy penalty of using more glazing than was otherwise necessary.

Options 3 and 4 delivered more light than necessary and required translucent glazing to control direct sun during many operating hours, resulting in higher solar loads and greater glare probability.

Option 5 proposed northwest-facing roof monitors which block direct sun for most operating hours. Daylight levels met the lighting objective for most of the year with imperceptible glare levels and an efficient use of glazing.

In the design development phase, option 5 was chosen. Further daylighting simulations were used to investigate any effects of the refined skylight geometry and more detailed glazing selection. The updated simulation showed that the high overall performance was maintained while the Tvis was able to be reduced to 60%.

8.8 ANNUAL DAYLIGHT GLARE PROBABILITY

Annual Daylight Glare Probability simulates glare each hour (or other time-step) of the year from a specific viewpoint within a space. This can be used to predict times when blinds will be closed manually, or when automatic shades will be deployed. It can also be used as a basis for a lighting or blind schedule for a whole building or shoebox energy model.

Project type:
2-story lab

Location:
Great Lakes Region, USA

Design/modeling firm:
Skidmore, Owings & Merrill, Chicago

Overview

Roche Pharmaceuticals required that critical program areas be daylit for aesthetics, performance and health in their new 2-story lab building. The design team proposed a top-lit atrium in the concept phase that would allow views and daylight through the entire cross section of the building.

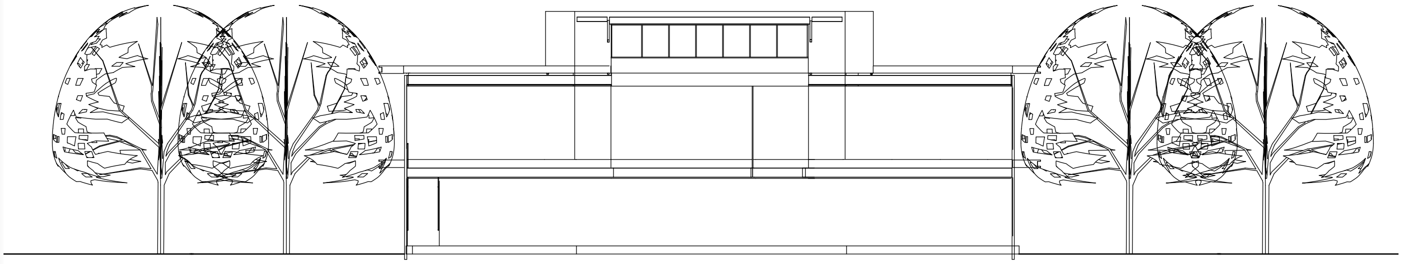
For the side-lit areas, annual Daylight Glare Probability (aDGP) analysis was used to estimate the value of using a row of trees to reduce glare while meeting illuminance targets. This study did not seek absolute accuracy but rather a basis of comparison between different tree locations.

The goal of daylighting is to provide quality daylighting without glare, and especially to reduce lighting energy use and associated cooling loads. When glare is present in workspaces, daylighting fails—either occupants close the blinds and turn on the lights, or the automatic systems do it. This study looks at the potential to reduce energy use by allowing good quality and quantity of daylight while blocking glare with trees.

8.52

Rendering at entry.

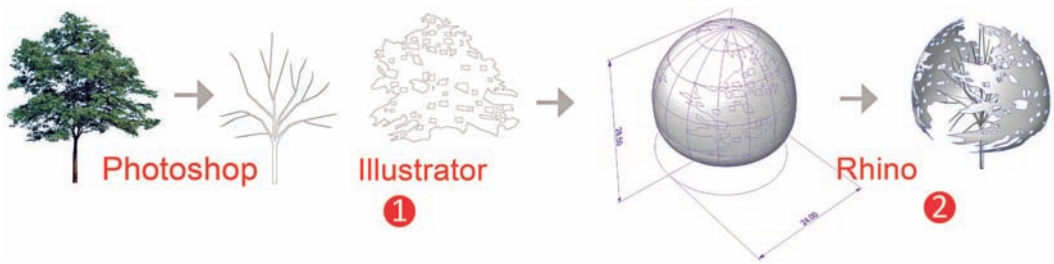
Courtesy of Skidmore, Owings & Merrill, Chicago.



8.53

Sectional line drawing looking south, showing trees at two potential distances from the façade.

Courtesy of Skidmore, Ownings & Merrill, Chicago.



8.54

Creation of digital tree geometry.

Courtesy of Skidmore, Ownings & Merrill, Chicago.

Simulation

This simulation was performed by SOM's Design Performance Group, which specializes in early design simulations. The Revit-based model was imported and re-built in Rhino for this tree canopy study in the design development phase.

Research was conducted into modeling and defining the optics and seasonal behavior of a Thornless Honeylocust to create a simulated tree. A vector outline (1) of the species was projected onto two sides of a 3D volume. The canopy openness was approximated in the Rhino model (2) to allow direct, dappled light from various directions and a variation of light passing through and reflecting off leaves. This approach reduced meshed surfaces and simulation time.

Research and guidance from Christopher Meek at the University of Washington Integrated Design Lab (IDL) into the optical properties (3) of the leaves were used to create a Radiance material (4) for the leaves using Optics 6 Software. The tree leaves were scheduled to be present in the model between May 15th and October 15th to simulate deciduous vegetation.

Annual DGP simulation was performed using the Diva for Rhino plug-in with packaged programs Radiance, Daysim and Evalglare. Each annual run took 1–2 days of run-time.

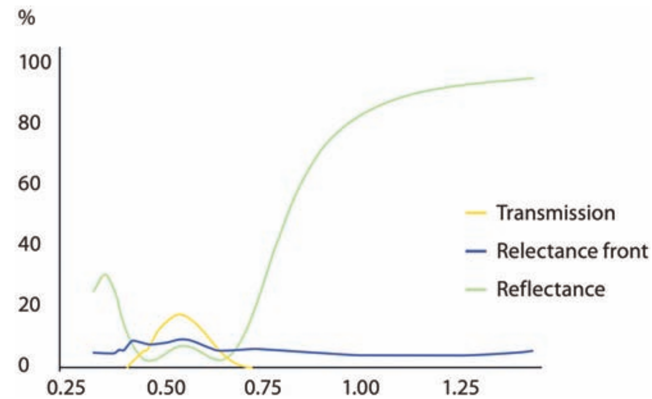
Annual illuminance levels from Daysim were sorted into several categories (5) to evaluate potential glare: greater than 2000 lux; useful daylight illuminance 300–2000 lux; and daylight autonomy >300 lux. These thresholds were chosen based on the research of Mardaljevic and Nabil (2005), and Reinhart and Walkenhorst (2001). A 10% reduction factor in daylighting was used since mullions were not included in the geometry.

Material reflectances were set as: ceiling = 80%, wall = 50%, floor = 20%, Ground = 15%.

Interpretation

Annual DGP was simulated in Diva to characterize hourly glare from a viewpoint in the perimeter zone looking outdoors (6) for the 30′0″ option. The study showed the value of trees as high-performance, seasonal glare-controls. While the southwest façade otherwise experienced intolerable glare nearly year-round in the afternoon, leading to blinds being deployed, the trees significantly reduce all types of glare throughout the year.

Analysis showed daylight levels and glare potential increase as the trees are moved further from the building. The 30′ tree-to-building spacing achieved daylight targets, with 47% of operating hours receiving between 300–2000 lux. It was chosen for the landscape design based on this study and the constraints of the site.



4 # Tree leaf material_Transmittance= 0.134

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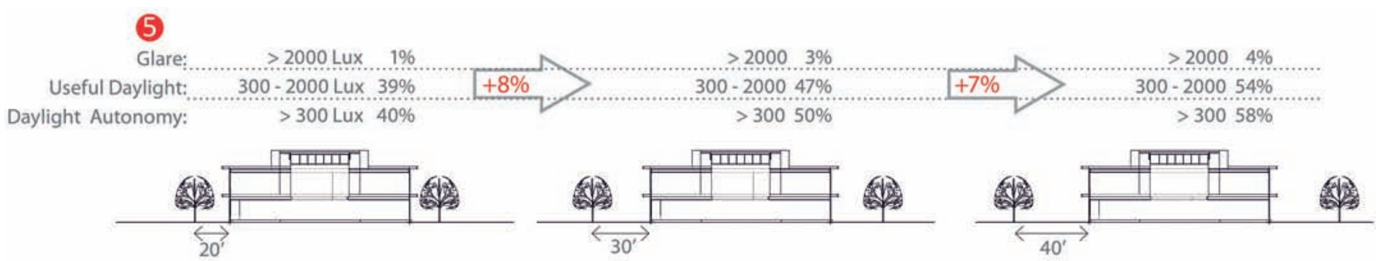
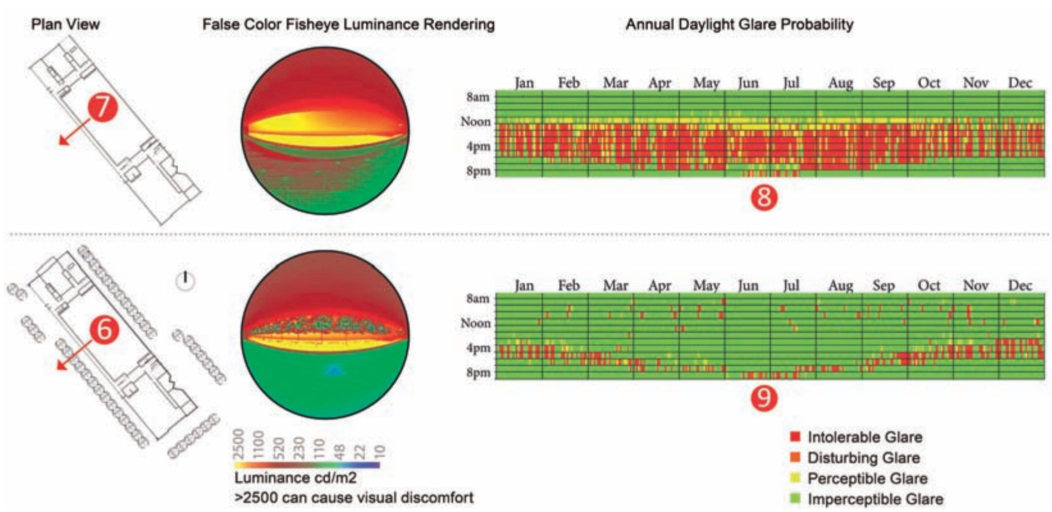
void glass leaf_description
0
0
3   0.068   0.183   0.086
```





8.55 Leaf optical properties wavelength (microns).

Courtesy of Skidmore, Owings & Merrill, Chicago.

8.56 (in image).

Courtesy of Skidmore, Owings & Merrill, Chicago.

8.57 Daylight and glare at various building-to-tree distances.

Courtesy of Skidmore, Owings & Merrill, Chicago.

8.58 Annual DGP results.

Courtesy of Skidmore, Owings & Merrill, Chicago.

A baseline option (7) was run with no trees for comparison. The baseline option is exposed to intolerable glare throughout the afternoon all year (8) due to direct sun and high contrast in the field of view. The proposed option with trees successfully controls glare up until sunset with less direct sun and lower contrast in the field of view (9). This schedule can be fed into blinds schedules for annual lighting energy use estimation.

9

Airflow Analysis

The pessimist complains about the wind; the optimist expects it to change; the realist adjusts the sails.

—William Arthur Ward

A chilling breeze on an otherwise pleasant wintery day, or the refreshing feeling of air movement from a slow, overhead fan on a hot, summer day, convey some of the effects of air movement on comfort. In addition to warmth or coolness, air carries humidity, odors, pollutants, and sounds.

Airflow analysis can be used in buildings to determine the following:

- natural ventilation airflow for fresh air delivery;
- natural ventilation cooling effects on comfort, using the stack effect or cross-ventilation;
- detailed thermal transfer via convection, including the effectiveness of displacement ventilation, underfloor air distribution, and double-skin façades;
- stratification;
- smoke evacuation and pollution control, indoors and outdoors;
- outdoor plaza and street velocity magnitude to predict discomfort, as well as avoidance of vortexes and wind canyons.

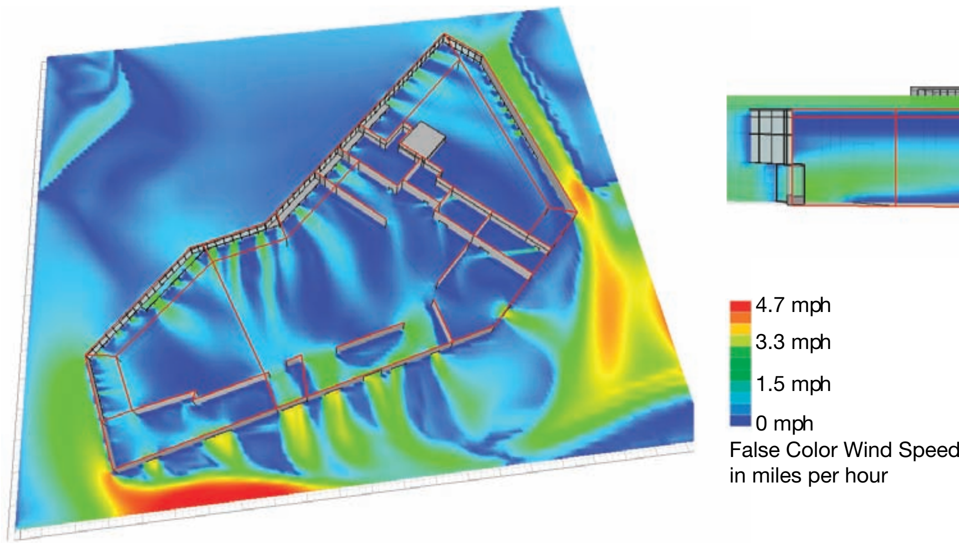
This chapter and its associated case studies focus on natural ventilation as it is a primary strategy in low-energy buildings during mild seasons. Natural ventilation occurs when airflow is channeled correctly through a building; it can cool a space, provide air movement to increase thermal comfort, and provide fresh air.

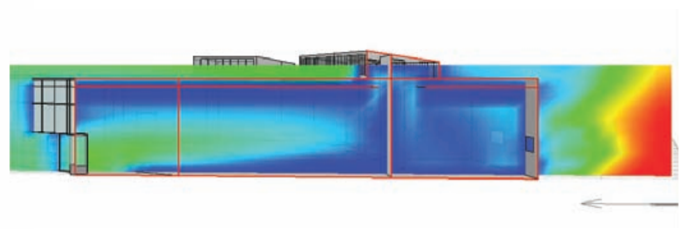
As the developing world builds at a frantic pace, they are abandoning naturally ventilated buildings just as the developed world is re-discovering them. Air conditioning systems use electricity from coal-based power plants which contribute to global warming, and the refrigerants that cooling systems require have additional global warming effects when they are released.

Airflow analysis is one of the most important pieces missing from current energy modeling efforts. While airflow analysis and natural ventilation is based on sound scientific principles just as mechanical systems are, the science behind them is not as widely understood or taught.

Software companies are putting air velocity analysis for building exteriors within reach of architects. However, architects are not trained to set up or interpret most other airflow models, which are still only in the realm of specialists. This chapter is included to shed light on the airflow analysis process and terminology so that architects can engage more fully in the design of their buildings.

Most energy analysts use software that has, at best, rudimentary consideration of airflow. In the past, project teams have studied airflow using wind tunnels or Computational Fluid Dynamics (CFD) software, which requires extreme specialization and only simulates conditions at a single point in time. Contemporary software, combined with increasing computer speeds, allows a wider variety of investigations into airflow that are required to design and validate design strategies that rely on airflow.

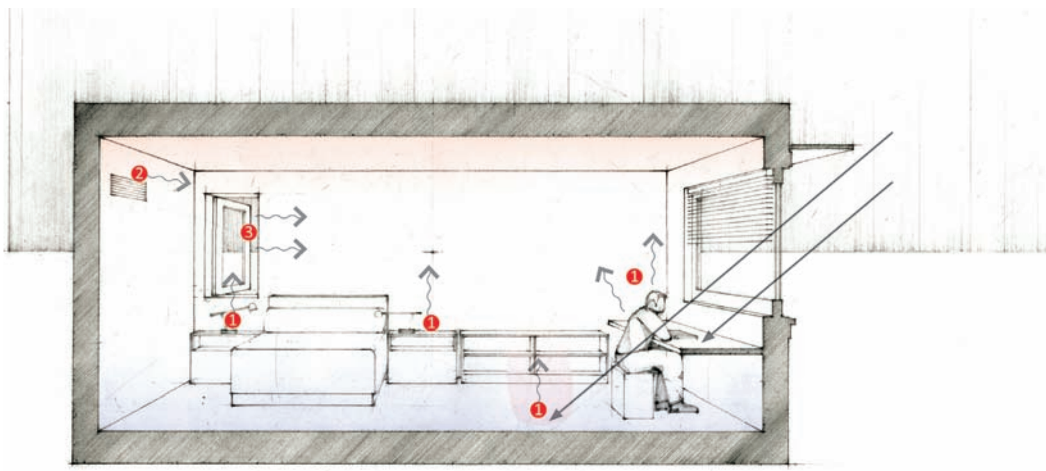




9.1

A computational fluid dynamics (CFD) airflow analysis through DPR Construction's Net Zero Energy San Diego office showing wind velocities through the open office and conference room spaces in plan and section. CFD was used to verify the potential for natural ventilation to provide adequate cooling even when outdoor windspeeds are low.

Source: Courtesy of KEMA Energy Analysts.



9.2

Airflow within a room is created by multiple sources air rising from (1) heat sources (such as a lamp, person, or a floor warmed by solar irradiation) due to buoyancy creating thermal stratification (red and blue overtones); the interactions of forced air from a (2) fan or a mechanical system and (3) outdoor air speed and direction, channeled by building geometry into and out of a room.

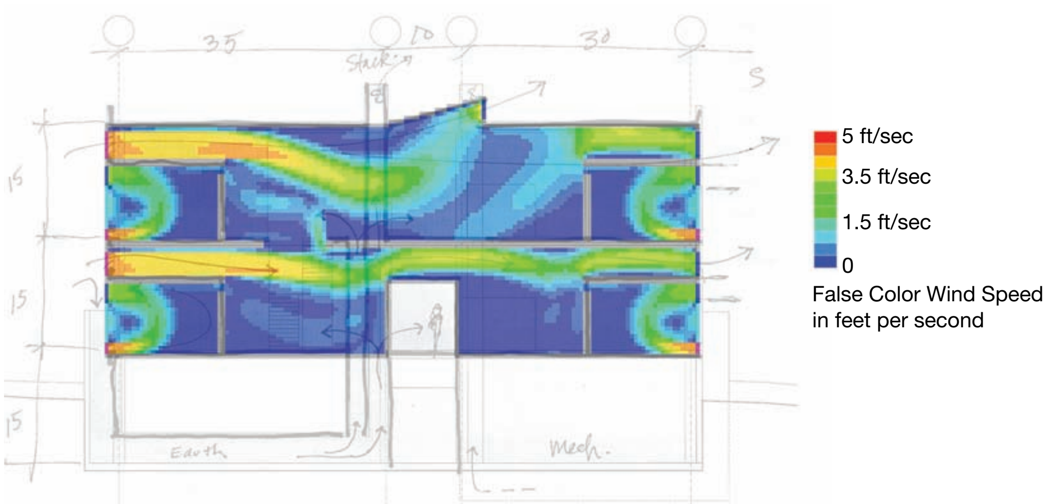
NATURAL VENTILATION AND MIXED-MODE OPERATION

Natural ventilation channels direct outside air to do one or more of the following: provide fresh air, provide cooling, or provide airflow to increase human comfort levels. The ability to use natural ventilation depends climate-wise on peak interior temperatures, and the humidity, solar radiation, and wind directions associated with those temperatures.

Geometry that allows natural ventilation needs to be set out early in the design process so that airflow into, through, and out of the building is assisted and not hindered. In many cases, orienting a building for wind or sizing stacks properly, incorporating operable windows or trickle vents, using a narrow floor plate, and controlling of peak loads are enough for conceptual design efforts. Studies later in the design process can refine any elements and determine comfort levels.

For example, offices at the University of Washington Molecular Engineering Building were designed without air conditioning, using no airflow modeling until the design development stage, as described in Case Study 9.2. Urban buildings, tall buildings, and complicated geometries require airflow analysis earlier in the process to ensure the success of natural ventilation. As a design progresses to where mechanical systems and ductwork are being reduced or eliminated due to natural ventilation, airflow analysis becomes essential.

Mixed-mode buildings use natural ventilation for cooling part of the time, and for fresh air a larger percentage of the time. They use mechanical heating and cooling during less ideal times. All four Net



9.3

An airflow simulation through a building section showing inlets, outlets, and airflow between them based on simple geometry. LMN Architects produced this 2D Airflow simulation using 2D Tas Ambiens by IDSL and a step-by-step how to guide is found on their blog: http://lmnts.lmnarchitects.com/featured/tas-ambiens/#.UPLgeB37J8E.

Zero Energy (NZE) buildings described in this book are mixed-mode buildings in marine climates, where mild summer breezes can often offset internal loads. However, natural ventilation works during mild seasons in nearly every climate. Case Study 9.3 illustrates a building with five operational modes that are employed under different outdoor conditions.

Natural ventilation is difficult to use when outdoor pollutants or noise levels are high and during hot periods with high humidity. With no ductwork, air filtration is difficult in naturally ventilated spaces. The project teams for Case Studies 9.1 and 9.3 specifically oriented their buildings to allow natural ventilation while minimizing noise and pollution.

TERMINOLOGY AND CONCEPTS

The two methods of powering natural ventilation—using wind or stacks—are described below, as well as other basic terminology and concepts related to airflow simulation.

Cross-ventilation is designed mostly in plan view, where windows on opposite sides of a space are used to control and channel prevailing breezes through a space. It uses geometry to create differential pressures on differing sides of a building, which sucks air into and through a building.

Stack ventilation is designed in section view—it relies on warmer air rising, referred to as *buoyancy*. Buoyancy is every bit as scientific and predictable as forced air systems, though much less often simulated within the design process. Air heats up in a space due to the warmth emitted from people, lights, and equipment.

In spaces conditioned by forced air mechanical systems, *mixing* of supply air and room air is necessary, requiring constant fan energy use. Low-velocity systems, radiant systems, and naturally ventilated spaces usually allow the air to stratify, reducing fan energy use.

In stack ventilation, the air is allowed to stratify, with the warmer air being channeled upwards using a vertical 'stack' or atrium. As the warmer air rises and exits through the top of the stack, cooler air is drawn in at the lower level. Stack ventilation can be assisted by a solar chimney at the top or fans when outdoor conditions do not naturally drive it.

Stratification can have a positive effect in high-ceilinged spaces in hot climates (such as cathedrals in Spain)—the warmest air naturally rises while the air near occupants is much cooler. Displacement ventilations systems, including underfloor air distribution, rely on stratification to reduce the amount of energy used by fans to supply and mix air for each space. Stratification has a negative effect in high-ceilinged spaces during cold periods. Since the warmest air rises, more heat is necessary to maintain comfort at lower levels unless fans continuously prevent stratification. A large de-stratification fan in the Rice Fergus Miller offices (Case Study 1.1) ensures that air is well-mixed in the triple-height space, reducing heating energy demand during the winter in the lower spaces.

Airflow that is not near objects tends to be smooth and directional, called *laminar flow*. When laminar flow is disrupted due to encountering objects or reaching higher velocities, it becomes *turbulent flow*. Direction and speed are very difficult to predict in turbulent airflow without CFD software or wind tunnel testing. For this reason, urban areas are prone to turbulent airflow from the combination of adjacent buildings with simulation required to determine the effects, see Case Study 9.4. The layer of air between the object and the outer edge of turbulent flow, where it subsides into laminar flow, is called the *boundary layer*.

All airflow simulations need a geometric boundary, outside of which no calculations are necessary. A larger boundary can potentially increase accuracy but increases run-time. For exterior CFD simulations, the boundary is usually a box that includes a solid ground and "air" walls and ceiling that extend well beyond the building geometry in all directions, often three times the largest dimension of the area being studied. Interior simulations use the solid boundaries of one or more interior spaces.

To create the simulation, air is directed by the user to flow into and out of the simulation at various locations. In most cases, air will flow into and out of the simulation from the boundary edges described above. For outdoor simulations, a single airspeed and direction are chosen, which flow into or out of all boundary walls. For interior simulations, the user defines the boundary edge inlets and outlets. Each inlet and outlet can have a unique air speed and volume, but the total volume of air entering the simulation needs to be equal to the volume of air leaving it.

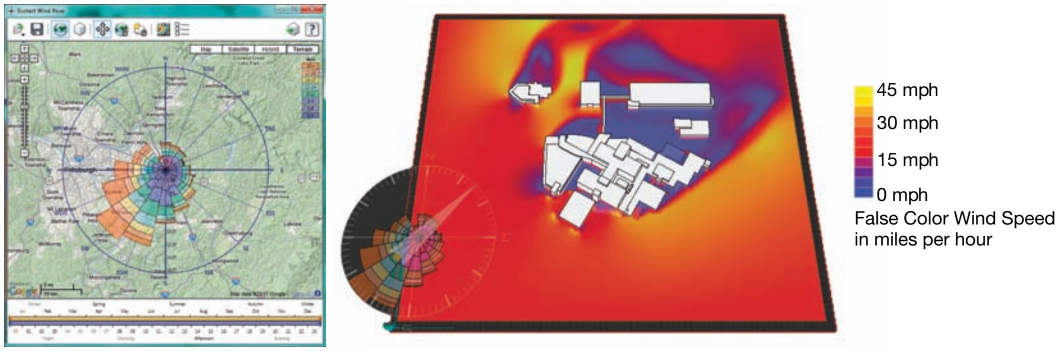
METHODS OF ANALYZING AIRFLOW

Computer-based airflow analysis for design can be divided into two categories: computational fluid dynamics (CFD) and bulk airflow. CFD results in a point-in-time (PIT) analysis that requires very complex, iterative calculations to achieve a single result. Bulk airflow analysis is part of some energy modeling software, often calculated as an average airflow and temperature over an entire hour. Similar to PIT daylight simulation, CFD allows a high degree of accuracy but limited time frame, whereas bulk airflow is useful for daily or annual analysis but involves less detail than CFD.

For DPR Construction's Newport Beach offices, which included minimal exterior work on an existing building, KEMA Building Performance Analysts used CFD modeling to determine the airflow effects of adjacent buildings. A thermal model using bulk airflow analysis was then set up using inputs from the CFD model to anticipate the cooling provided by natural ventilation and determine the number of operable windows necessary to ensure comfort. See Case Studies 9.4 and 10.6.

Computational fluid dynamics simulates how gases or fluids flow through or around objects. It encompasses a large and complex body of research and algorithms that help design spacecraft and artificial hearts, and can predict airflow around and within buildings. Architectural CFD is concerned primarily with aerodynamics—the study of air movement. References to CFD in this chapter will focus on air as the "fluid."

Simple CFD analyses calculate only air speed and direction in two dimensions. Predicted wind speeds are compared to comfort charts to determine if design measures are required to mitigate uncomfortable wind effects. The most frequent directions and velocities need to be tested to ensure a robust design.



9.4

A 2D airflow analysis around and through a building cluster using interactive computational fluid dynamics (CFD). The wind rose advises the user where wind is likely coming from and typical windspeeds. In this case, 24 miles per hour was used as the input windspeed. While the results on a computer look like an animation, the software needs to iterate 50 or more times to determine the right result for wind coming from a given direction and speed. The animation will eventually reach a steady state, which is the solution for the user's input.

Source: Courtesy of Astorino Architects.

Wind inputs are chosen by the user, but can be taken from weather file, local weather station data, or a wind velocity based on wind tables to test performance under an expected or critical condition.

More complex analyses consider air speed and direction in three dimensions. The most complex models incorporate every heat-producing element within a space: lights, people, equipment, surfaces, and solar irradiation. Each heat load creates airflow around it due to convection. The airflows interact with each other, removing or depositing heat on every surface they touch. Calculations consider mass transfer, phase changes, mechanical air movement from ducts and fans, and other variables, making them highly complex.

For all CFD simulations, equations must be solved simultaneously for each of hundreds or thousands of 2D or 3D grid points throughout a space. This requires many iterations in order to achieve a single, point-in-time solution. For reasons of computational run-time, only a single zone or limited area is modeled at a time. Due to the long set-up and run-times, the question being answered through the simulation needs to be more tightly defined than for other simulation types discussed in this book.

The equations are complex enough that in some cases, physical simulations work best. Physical simulations use colored air and photos or video to interpret wind flows and vortexes around solid objects, requiring specialized equipment.

Bulk airflow analysis is a less computationally intensive method, but it allows daily or annual analyses of airflow effects on heat transfer and comfort. It includes hourly analyses for mechanical airflow, natural ventilation, heat loads, buoyancy, and stratification. Bulk airflow analysis requires dividing a space into zones that have relatively uniform temperatures, which is covered in Chapter 10.

Bulk airflow analysis does not consider interior obstructions and heat sources with the degree of accuracy that CFD allows, but is perfectly adequate for most natural ventilation simulations. Since bulk airflow analysis can be integrated into energy modeling software, the inputs can be the same as those covered in Chapter 10 on Energy Modeling, except that spatial distribution of heat sources is necessary.

CONCLUSION

While airflow analysis is not part of most building simulations today, it is part of nearly all low-energy buildings. Natural ventilation provides energy-free fresh air and cooling that work in many climates. It is most often used as part of a mixed-mode design where it operates when outdoor conditions are relatively mild.

The case studies in this chapter include efforts by architects and engineers. They include two Net Zero Energy buildings, another without mechanical cooling, and one that re-used an existing building and mechanical system, reducing the need to use the mechanical system by 65% by incorporating natural ventilation.

9.1 NATURAL VENTILATION ANALYSIS WITH CFD

When natural ventilation is used as a cooling strategy, the comfort it provides needs to be proved using physical models or computational fluid dynamics (CFD) studies. While CFD studies have been beyond the ability of most architecture firms, software is becoming easier to use and more automated.

Project type:
Single-story library

Location:
Berkeley, California

Design/modeling firm:
Harley Ellis Devereaux

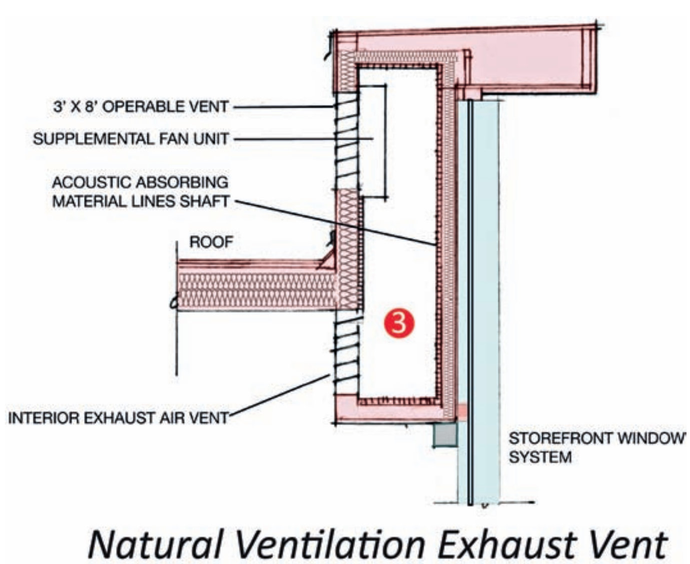
Overview

This 9,400 sf library for the City of Berkeley targeted Net Zero Energy (NZE) in concept design. The amount of available photovoltaic and solar thermal production on the rooftop required the project team to target EUI of around 15 kBtu/ft^2/year.

Low-energy design necessitated good daylighting, plug-load reductions, and mechanical system efficiency. The mixed-mode strategy keeps the mechanical system off for much of the year while providing fresh air and most of the cooling within the library.

In Net Zero Energy buildings, the roof often becomes the project's densest design challenge: daylight, energy generation, and equipment compete for space. The West Berkeley Library roof design ingeniously balances the desire for optimally oriented photovoltaic panels, skylights for daylighting and ventilation, and a wind chimney that allows through ventilation without any ventilation openings facing the noisy street to the south.

The design team knew that natural ventilation could provide most of the space cooling based on local design experience. However, five modes of operation were necessary in order to ensure comfort year-round. While the building will potentially use multiple modes within a given day based on outdoor temperature and wind speed, the predominant modes of operation are considered for annual energy use predictions.

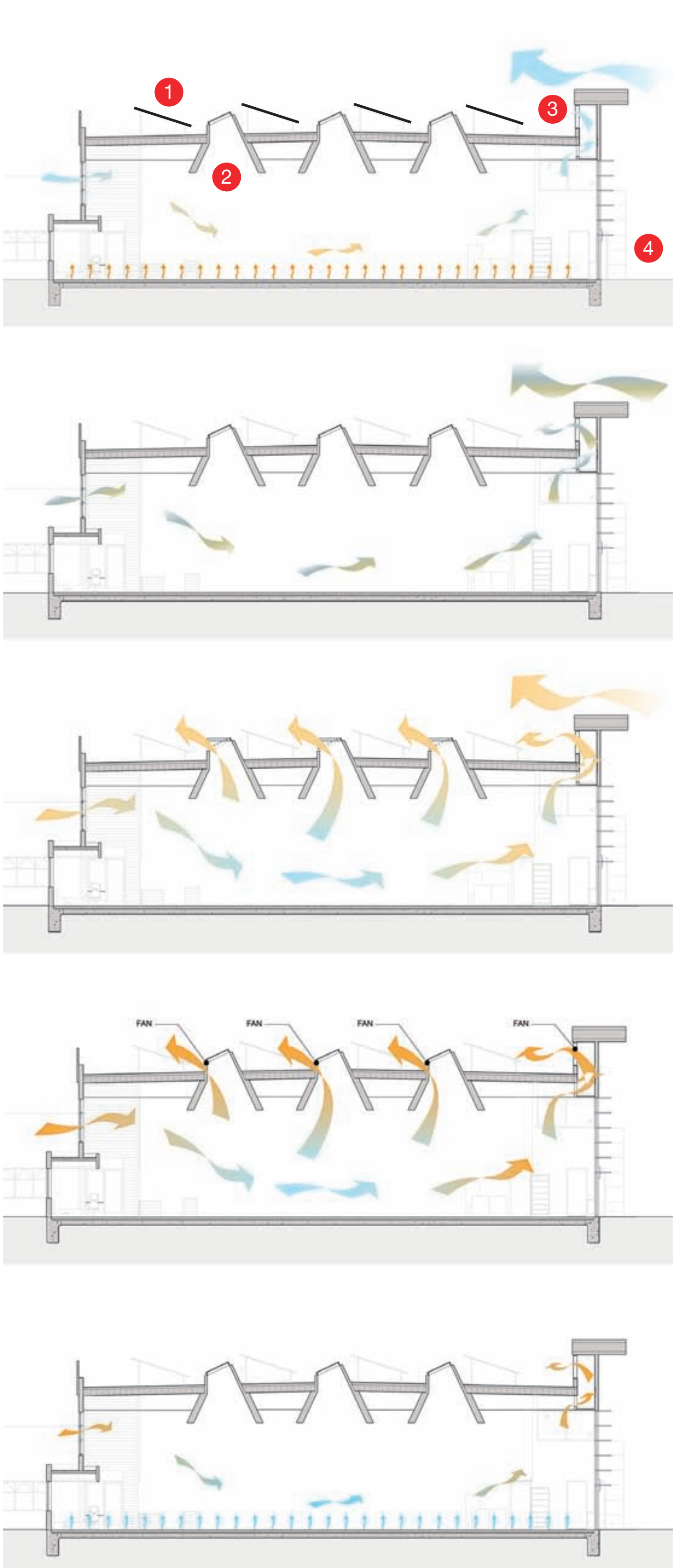


9.5

Natural ventilation exhaust vent.

9.6

The five modes.



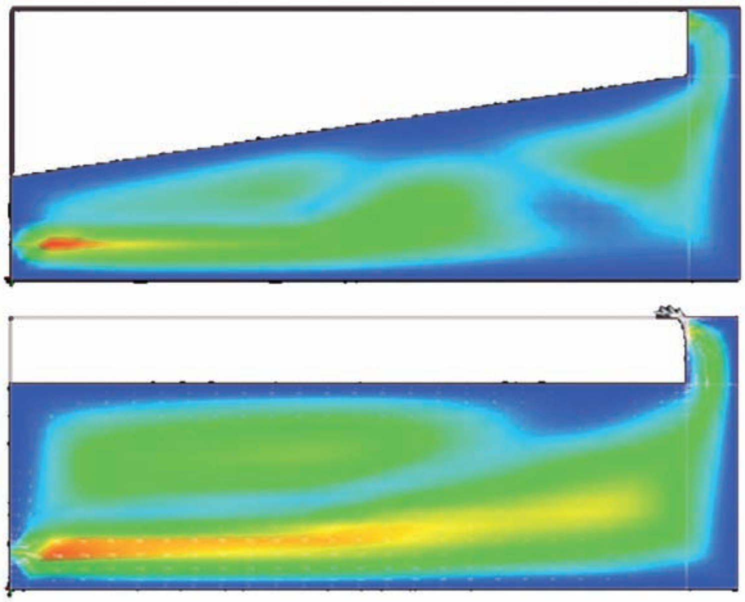
Mode 1
Heating Season. Minimum outside air admitted.

Mode 2
Swing Season. Outside air quantity varies to provide cooling and fresh air. Wind chimney only.

Mode 3
Early Cooling Season. Cooling via wind chimney and venting skylights.

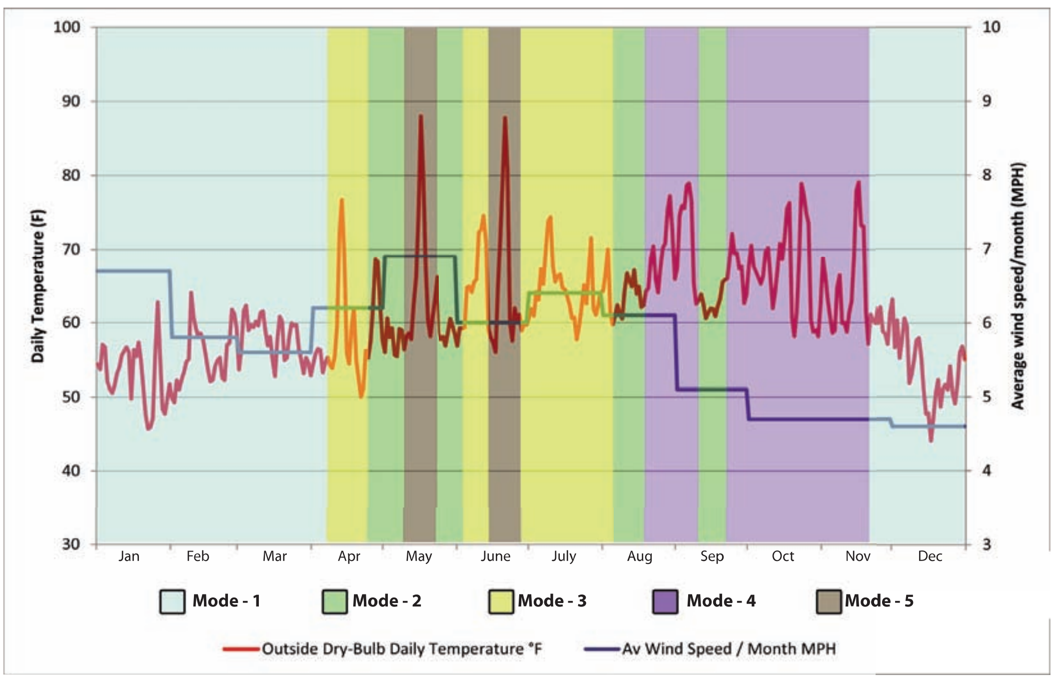
Mode 4
Cooling Season. Skylight roof fans maximize outdoor air for cooling. Nighttime purging as necessary.

Mode 5
Peak Cooling. Minimum fresh air. Cooling provided by radiant slab.



9.7

CFD studies to determine if a sloped or flat ceiling affects the cooling airflow near the floor level.



9.8

Predominant modes of operation are based on outdoor temperature, windspeed, and wind direction. While the building will often use more than one mode each day, the predominant mode for each day is shown here based on the TMY file used for energy modeling.

A busy street on the south façade meant air intakes in this direction would admit noise and pollution. Instead, the street façade was extended vertically to include a passive air exhaust, referred to as a wind chimney. Since the predominant breezes are from the south, the verticality of the wind chimney creates negative pressure behind it, consistently drawing air out through it.

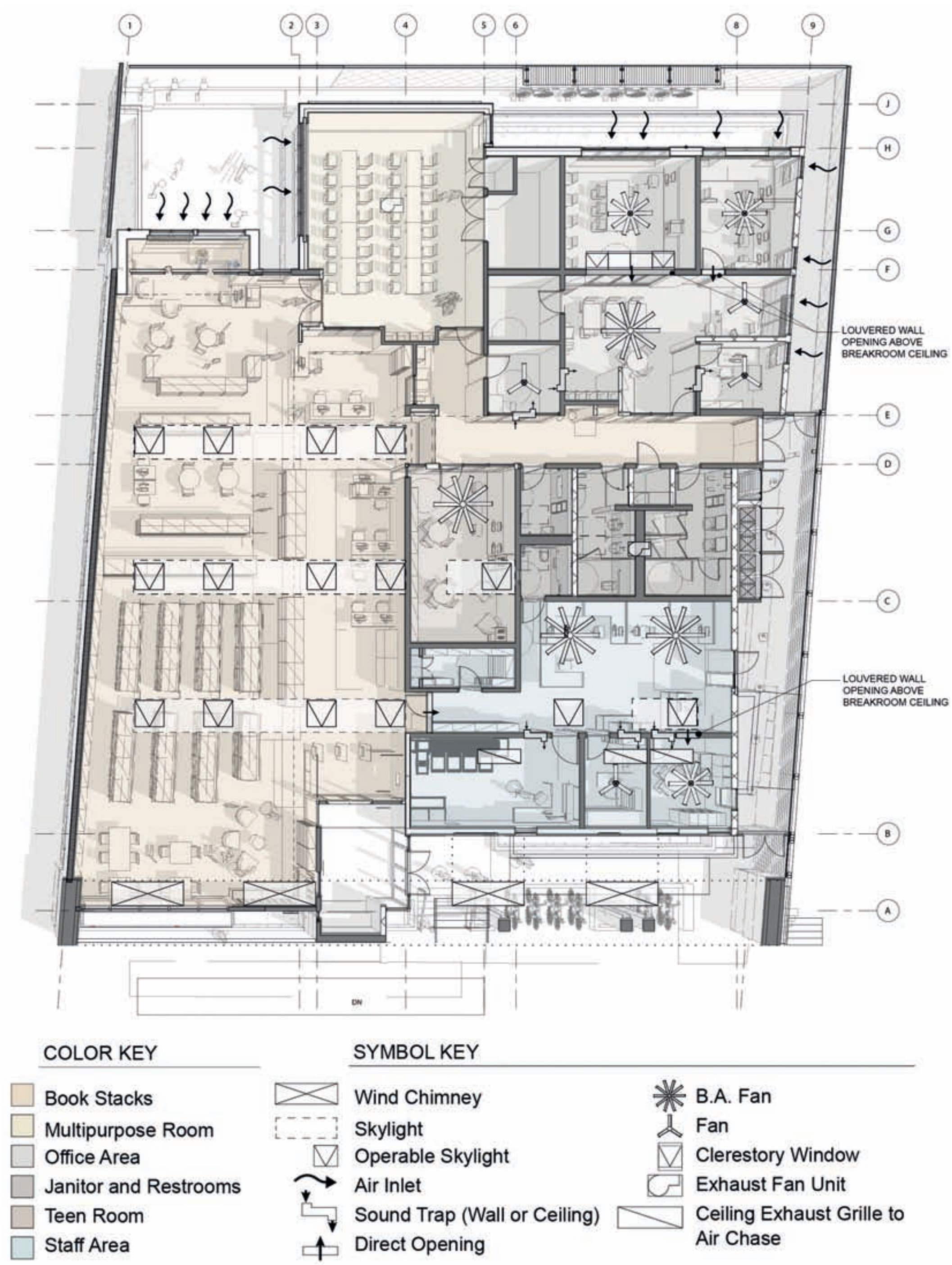
Mode 1: A minimal amount of fresh air is allowed in through the building during the heating season. The air is heated using hydronic radiant panels near the air inlets.

Mode 2: During the swing season, varying amounts of air are allowed in to maintain fresh air levels and comfortable temperatures using the wind chimney.

Mode 3: During part of the cooling season, air is allowed to vent out of the daylight wells in the roof as well, providing more cooling than in Mode 2.

9.9

Floor plan showing layout of airflow systems.



Mode 4: When the previous method cannot provide enough cooling, or when the breezes do not provide enough negative pressure behind the wind chimney, the skylight vents are closed and fans are used to maximize airflow and associated cooling in the main library space.

Mode 5: During peak periods, the heat pump is run in reverse to provide cooling, with a minimum of fresh air being circulated through the space using the wind chimney.

Simulation

Design of the roof features, which include photovoltaics, solar thermal, daylight wells, natural ventilation exhausts, and a wind scoop, was done primarily using past experience with design and simulation, which was verified during schematic design.

The main public reading room and stacks are within a high-ceiling space to allow for daylight distribution. However, the design team was unsure whether the high ventilation opening would draw the cool air up and out before it could provide space cooling for people, near the floor level. A second airflow study was done to determine if the ceiling shape had a major effect on airflow and cooling.

The two-dimensional CFD simulation was done using Airpack v2.1.12. The sectional room geometry was used, along with the wind chimney geometry. The results showed that the ceiling shape did not significantly impact the airflow, and the cooling breezes settled near the floor level before they were drawn out through the wind chimney or skylights.

Additional Studies

Bulk airflow analysis was also performed using DesignBuilder software to size the ventilation chimney. While the wind chimney expression is continuous along the south façade, only 20% of its length is actually needed to provide adequate airflow and draw.

9.2 NATURAL VENTILATION USING THE STACK EFFECT

Project type:
Research lab and offices

Location:
Seattle, Washington

Design/modeling firm:
ZGF Architects/Affiliated Engineers, Inc./ SOLARC Engineering and Energy + Architectural Consulting

Natural ventilation that uses cross-ventilation often requires a single-loaded design; with properly sized stacks, however, double-loaded designs can incorporate effective natural ventilation.

Overview

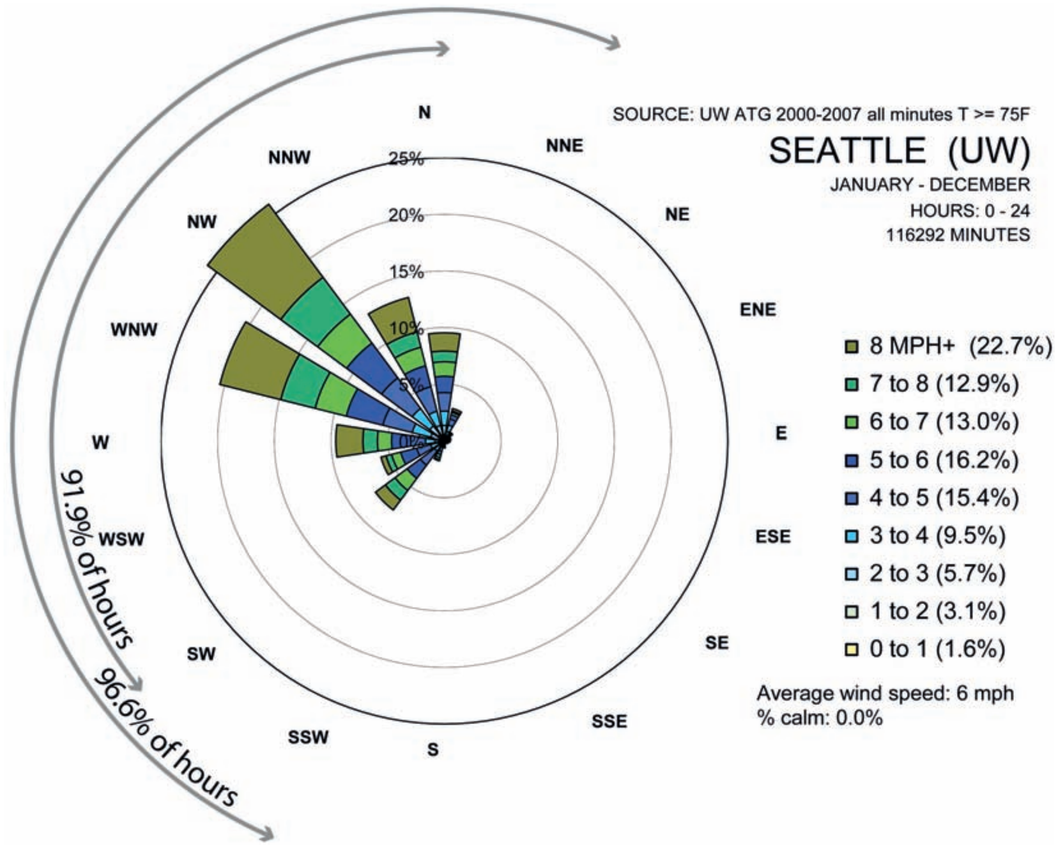
The University of Washington's new Molecular Engineering facility was designed to house cutting-edge interdisciplinary nanotechnology research laboratories and associated faculty offices in an anticipated LEED Gold building. Early in the design, the university expressed an interest in using natural ventilation for faculty offices. Recent attempts to eliminate mechanical cooling in campus offices had not materialized. Both the university and the design team saw natural ventilation not only as appropriate for this project and climate, but also as an exploration and precedent for future projects if successful.

Seattle's maritime climate lends itself to a natural ventilation strategy. The team confirmed the relevant climate parameters, using 30-year typical meteorological year (TMY) data from nearby Boeing and Sea-Tac airports, and correlated with eight years of weather data collected at the neighboring Department of Atmospheric Sciences.

9.10

Photograph of east façade.

Source: Photo © Benjamin Benschneider.



9.11

Wind rose for occupied hours where the outdoor temperature >75°F.

All three data sets showed that temperatures rarely exceed 80°F. The TMY file showed around 100 hours per year exceeding this threshold, while the campus data showed a range between 25 and 225 hours each year. In addition, hourly analysis showed that while summer high temperatures over 80°F occurred in the late afternoon in late summer months, temperatures the previous night typically dropped to 60°F or lower. Even on the hottest days, the late morning temperatures were still often below 75°F.

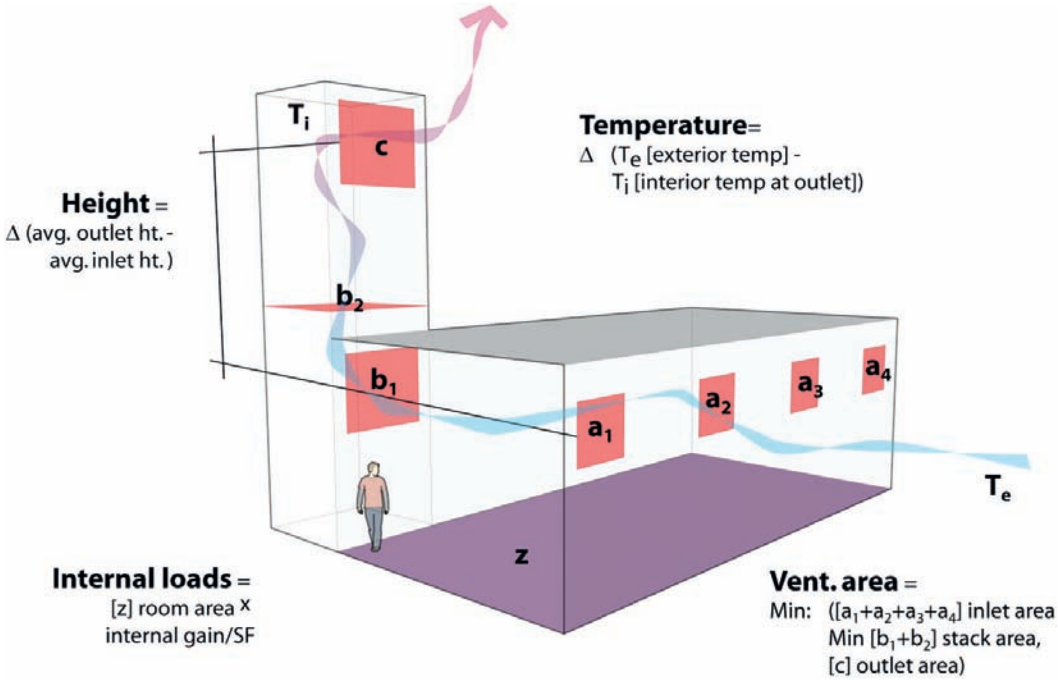
While summer winds came predominantly from either north or south, the Atmospheric Sciences data showed that winds were almost always from the northwest when temperatures exceeded 75°F.

Faculty offices and their lab benches were required programmatically to be across a hall from one another. Since lab benches require mechanical ventilation to control fumes, the nature of the building's program made cross-ventilation impossible.

Instead, the team settled on a strategy of stack ventilation, using the buoyancy of the warmer exhaust air to drive ventilation through vertical shafts in the middle of the building. The masterplan called for the building to complete the southwest side of the science courtyard, meaning primary orientations would be northeast and southwest. The labs were intended to be on the quieter northeast courtyard side. However, several factors led the team to switch the offices to the northeast: the prevailing breezes from the northwest would help drive natural ventilation in the offices, frequent bus service noise and fumes on the southwest would have diminished the desirability of operable windows on that façade, and the northeast orientation would reduce solar loads to the point where natural ventilation would be possible.

Simulation

ZGF and Affiliated Engineers, Inc., mechanical engineers on the project, worked with Mike Hatten and SOLARC, as energy modelers, to optimize the design for ventilation. Early design moves created the possibility for natural ventilation through orientation and location of the stacks.



9.12

Stack diagram showing the important inputs into a natural ventilation model.

Once design development started, the team began modeling the airflow to understand how peak cooling loads could best be met. This energy modeling effort first determined that peak cooling for the offices occurred in late July mornings, due to the combination of warmer mornings, longer days, and morning sun that rose in northwest. On these days, the energy model determined that the peak amount of cooling needed to maintain comfort was approximately twice that which could be accomplished through natural ventilation.

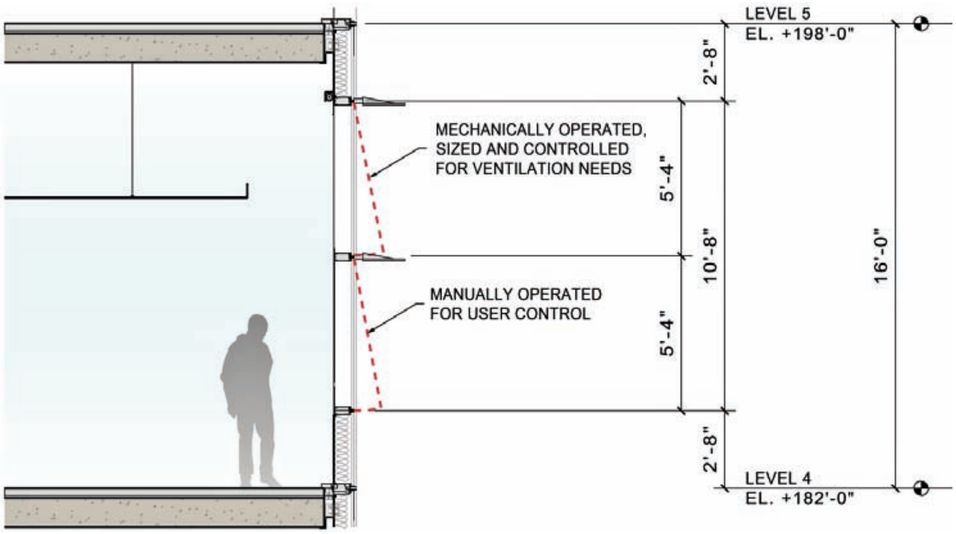
The team used iterative modeling to determine how best to reduce peak loads by 50% through façade design. The best strategies emerged through several rounds of energy modeling, shading, and daylighting studies.

The resulting façade reduces peak solar loads by reducing glazing area; using higher performance Solarban 70XL glass with a better solar shading coefficient; and fixed horizontal shading. Daylight modeling in Radiance confirmed that daylight would still be adequate in the occupied zone with the reduced glazing area, meaning that dimming ballasts could reduce or eliminate heat gain from electric lights during peak cooling periods.

Every floor was designed to have two independent stacks on at the north and south ends, located between the office and lab areas. The stacks on each floor were separate from other floors so that each would function independently and not short-circuit one another. Mechanically actuated windows in the upper daylight zone are sized to provide the necessary airflow to make the ventilation work. Manual operable windows in the lower view zone allow occupants to adjust local airflow and cooling to suit their preferences.

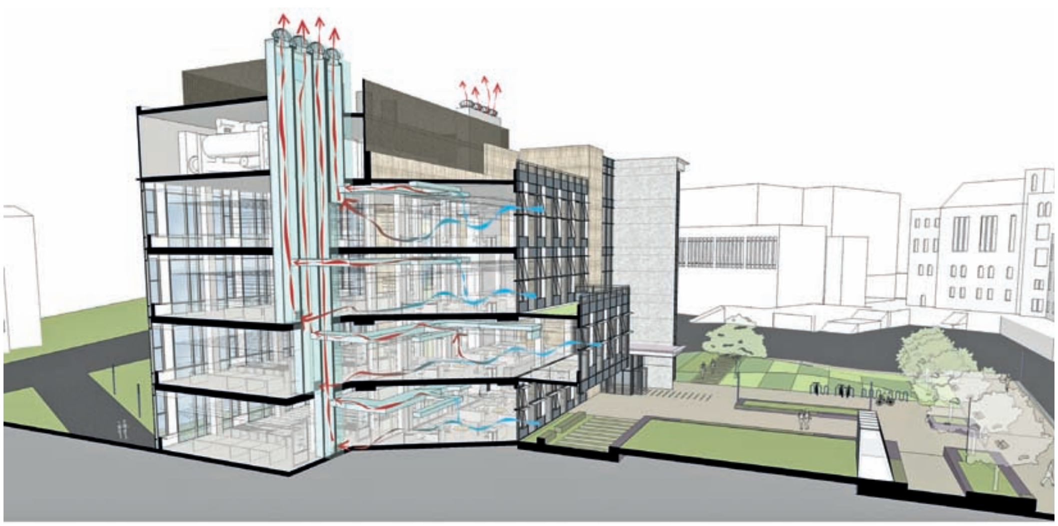
The building management system (BMS) reacts to interior and exterior conditions to adjust airflow through the windows and exhaust stacks, and airflow will increase as heat accumulates in the office to maintain comfortable conditions. At night, the BMS allows airflow through the building to cool the thermal mass and recharge the PCMs.

The buoyancy effect that drives stack ventilation is directly proportional to the minimum cross-section area of the stack that governs the airflow as well as the effective height of the stack. A single-zone bulk airflow model was used to size the cross-section and height of the stacks. It simulated the stack's effects on comfort, based on the peak heat gain and the requirement that inside temperatures would not be allowed to get 3°F above the exterior temperatures.



9.13

Section through window showing window uses and sizes.



9.14

Natural ventilation diagram showing airflow into the offices and up through each floor's stacks.

More detailed simulations were not necessary, as the stack exhausts incorporated a number of enhancements to airflow: "solar chimney" windows at the top of the stack super-heat the air which increases the airflow; turbine ventilators, which are driven by wind; and back-up electric motors to drive the turbines in case the airflow is not adequate.

CFD analysis was used to ensure that the worst-case effects of natural ventilation on laboratory exhaust would not endanger the safety of laboratory fume hood exhaust. In this study, lab doors were left open to the office, and the exterior laboratory envelope was modeled with a 1" gap across its length to simulate uncontrolled ventilation.

While there was a certain risk associated with designing offices without a dedicated cooling system, a number of additional measures were included to increase system reliability and enhance occupant comfort. The thermal mass of the concrete structure was exposed in circulation area floors and above hanging ceiling clouds. A phase change material, located in the ceiling clouds and in the walls of the private offices, provides thermal storage as well. The single-pane glass partition separating the labs from the offices provides radiant cooling via the glass, and make-up air due to the labs negative pressure flows through the non-lab spaces, meaning that some fresh air requirements are met without the comfort issues associated with natural ventilation during peak cold periods.

9.3 BULK AIRFLOW ANALYSIS

Project type:
6-story office building

Location:
Seattle, Washington

Design/modeling firm:
Miller Hull/PAE Engineering

Bulk airflow analysis can be used to predict natural ventilation's effects on internal temperatures and comfort levels. Instead of point-in-time (PIT) computational fluid dynamics analysis, bulk airflow analysis calculates each hour of the year to determine effects.

Overview

The Bullitt Center is a speculative office building that will house the Bullitt Foundation (grant provider for deep green research and projects) and other tenants. It is designed to achieve Living Building Challenge certification, including Net Zero Energy (NZE), plus Net Zero water, waste, among other goals. The Bullitt Foundation has been very transparent in sharing the detailed research and analysis required to design and construct a Living Building.

The Pacific Northwest climate is among the best for natural ventilation, where airflow can provide much of the cooling necessary for well-designed office buildings. Once peak loads are reduced to the point where natural ventilation is effective, studies on comfort and air-movement within the building are necessary.

The Bullitt Center's windows have motorized window actuators that are controlled by the Building Management System to provide ventilation at the right times during day and night. The windows are programmed to open around 4″ on all sides when the space temperature exceeds 70°F, unless the outside temperature exceeds the inside space temperature.

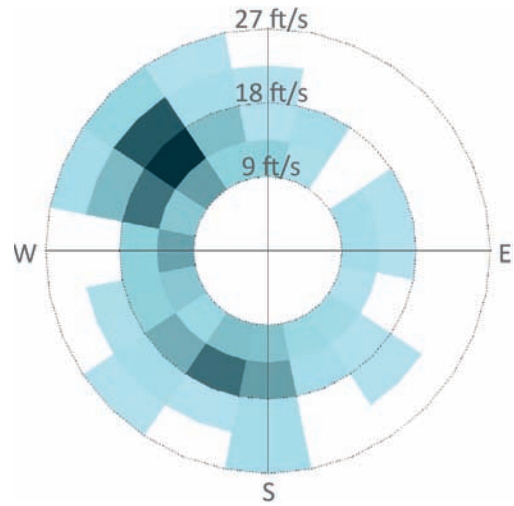
9.15

Rendering looking east.

9.16

Photograph of the type of operable windows used at the Bullitt Center. Window diagram shows equal opening size around window's perimeter to reduce wear and provide even, controlled airflow.

Source: Photo and diagram courtesty Shuco.



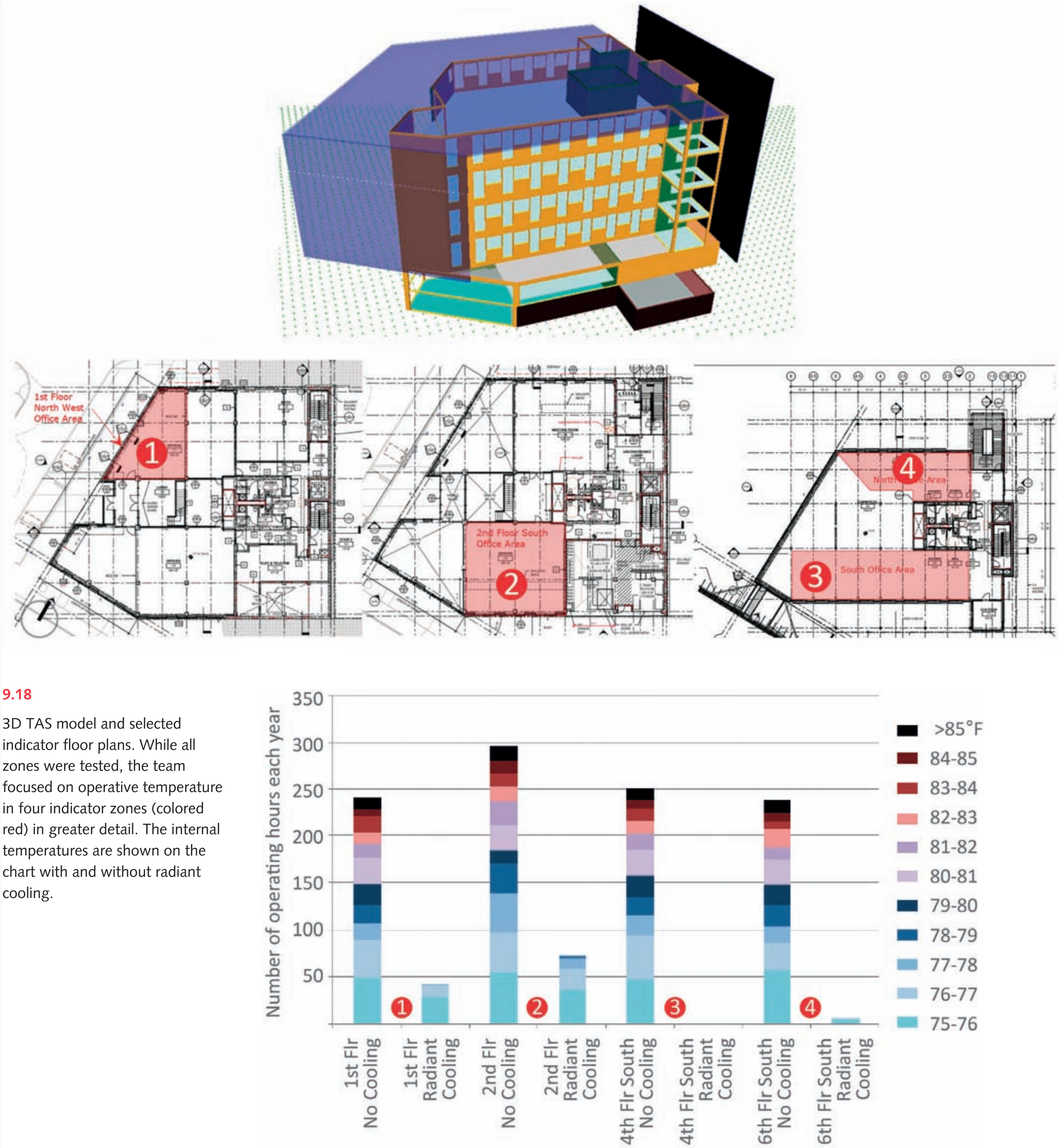
9.17

Wind rose for Seattle Boeing Field, showing frequency (darker color) of wind direction and velocity during summer afternoons.

A geo-exchange loop below the Bullitt Center primarily provides heating, but can also be run for cooling. The cooling is not sized to provide set-point temperature, but to temper the hottest days of the year.

Simulation

Bulk airflow analysis was used to perform hourly analysis of building loads to predict interior space temperatures—accounting for local weather, the building geometry and construction, the airflow into and out of the building through operable windows, the airflow between spaces within the building, and the anticipated use of the facility by its occupants. PAE Engineering modeled the entire building using



9.18

3D TAS model and selected indicator floor plans. While all zones were tested, the team focused on operative temperature in four indicator zones (colored red) in greater detail. The internal temperatures are shown on the chart with and without radiant cooling.

the thermal and airflow analysis software Bentley Tas v 9.1.4. Four typical zones were selected for detailed analysis to reduce the quantity of data presented to the design team.

The models used for the airflow analysis and the energy analysis were generated from the building's Revit model and used identical thermal zone layout. This approach allowed for an integration of the airflow data into the energy model to account for the natural ventilation airflows. The airflow model could have used a simpler zone layout than an energy model to reduce the setup time, and would have returned similar results. However, it was felt that the interoperability with the energy model made more sense for this project.

Once the airflow and energy models were developed, the design team used both models to test the effects of various façade designs on comfort and overall energy use. The particular strategies tested were: internal versus external shading, window insulation, visible light transmittance, and wall construction type and insulation. This analysis occurred throughout the design development and construction documents phases and, while documented, took the form of fairly informal collaboration between the architectural and engineering teams. This collaboration allowed for quicker turnarounds and decision-making while the architectural team designed the building's façade.

The final façade design includes windows with a 40% window-to-wall ratio, with about half of this window area being operable. The ratio of operable window area to floor area is around 2% on the office floors.

Interpretation

Thermal comfort is difficult to quantify and many different metrics have been developed that account for air temperature, humidity, air movement, radiant temperature, and clothing levels. The thermal modeling software accounted for all of these factors, plus radiant surface temperatures and local air speeds that contribute to occupant comfort and determine a PMV score.

ASHRAE's Mean Predicted Vote (PMV) is a common metric that accounts for these variables but it is not easy for the layperson to understand. Instead, to present their data, the design team decided to simplify comfort to just a dry bulb temperature, as it is a quantitative measure that all building occupants would be familiar with. A dry-bulb credit was taken for air movement, and humidity was not considered as a significant factor due to the dry Pacific Northwest summer climate.

The results of the comfort analysis showed that the high performance envelope, radiant slab and ventilation air cooling were expected to be capable of maintaining the space temperatures below 80°F in the studied zones. A "bin chart" was developed to graphically represent the number of hours that each zone's temperatures were expected to fall within 1°F temperature ranges throughout the year —both with and without radiant cooling. Without the radiant cooling nearly 100 occupied hours each year were shown to be >80°F in each zone. The relatively small amount of cooling provided by the radiant cooling was shown to eliminate nearly all hours above 80°F in this study.

Results from the DOE-2 energy study indicate the electricity requirement for ventilation and the radiant slab cooling to keep the space temperatures at or below 80°F is only about 5,000 kWh/year, or only about 2% of building energy.

Additional Studies

The airflow study was integrated with studies on nearly every aspect of the design, as achieving the project goals would not have been possible without simulation. Other examples of simulations performed for the Bullitt Center are given in Case Studies 7.5 and 10.7.

9.4 EXTERIOR CFD ANALYSIS

Project type:
Existing 2-story building

Location:
Newport Beach, California

Design/modeling firm:
Callison/KEMA Energy Analysts

Adjacent buildings can block or reduce the potential for natural ventilation within buildings. Testing exterior wind speed and direction using CFD can inform a bulk airflow model that estimates the ability of natural ventilation to provide cooling.

Overview

The Newport Beach Offices for DPR Construction were designed to reduce energy use significantly, with the resulting building 59% below California's stringent Title 24 baseline. Natural ventilation presented a significant energy-saving opportunity, so external wind studies were developed to explore the cross-ventilation possibilities. The computational fluid dynamics (CFD) study included here was done to test the impact on natural ventilation potential due to adjacent buildings to the north and east.

Wind roses for May, June, July, and August were considered, though only two are shown here. While winds come predominantly from the northwest throughout the year, they tend to occur from the southwest during peak cooling conditions. These were highlighted by overlaying a wind rose over the building, limited to the hours between 7 a.m. and 6 p.m.

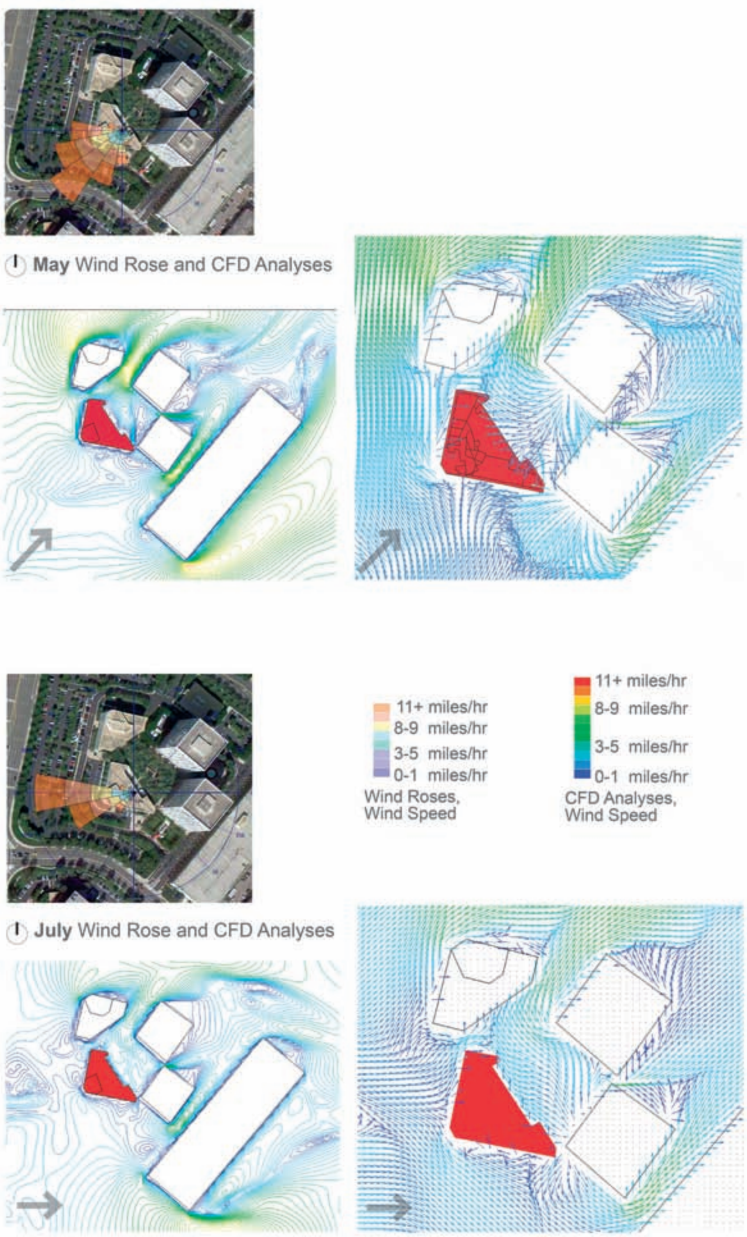
Simulation

For the CFD study, a geometric model of the existing building was created. Winds were tested in the cooling period, the months of May through August, at wind speeds between 2 and 3 miles per hour. This speed was chosen as a worst-case condition for airflow, since higher wind speeds would increase cross-ventilation possibilities. Many iterations of the most likely wind conditions were simulated from eight different directions.

Given the location of the adjacent buildings, the team guessed that a wind shadow (or negative pressure) would be created in the courtyard between the other buildings on site. This lower pressure zone would assist in drawing air through the space from the south and west façades through the building to the courtyard.

Although this does occur at times, the analysis showed that the major impact from adjacent buildings was to create eddies and wind gusts in almost every direction. As a result, and confirmed now that the building is occupied, the interior space does receive airflow from all directions during the peak design months. This conclusion helped to inform the team so that the number of operable windows retrofitted onto all façades could be minimized.

With natural ventilation potential proven at the site level, Case Study 10.6 on p. 216 shows how internal natural ventilation and other energy loads were used to produce a low-energy building.



9.19

Although several months were studied with CFD, only May and July are shown here with a wind rose overlaid on the site (key in faded colours), a CFD contour map showing pressures, and a 3D CFD map cut at 4′0″ above ground level showing wind directions at the studied velocity. The wind direction studied in each month is shown in light gray, based on prevailing winds, while wind speed was chosen at the low end of the average for that period.

10

Energy Modeling

Essentially all models are wrong, but some are useful.

—George E.P. Box

To achieve low-energy design, all elements that contribute to energy performance need to work in harmony. An energy model tests whether the interaction of these elements—climate, geometry, material properties, expected occupant behavior, lighting, and more—are working together to create comfort and achieve the project team's energy goals. Since architects lead the design process, they need to better understand the fundamentals of energy modeling.

If an integrated team approach is used, low-energy design can be achieved with less energy modeling in the early phases; engineers and other specialists can provide guidance based on their experience to lead the team down the right path. Unfortunately, the integrated approach is uncommon, and architects are left to explore and validate the effectiveness of selected sustainable strategies before the geometry gets locked in.

This chapter is intentionally placed towards the end of the book since it sums up and correlates the analyses done thus far. Climate, solar gain, daylight, airflow, and other aspects covered previously interact each moment of the day. In an energy model, heat gains and heat losses from each of these are summed to predict indoor temperatures. Mechanical or natural ventilation systems are then designed to add or remove heat to result in thermal comfort.

The first part of this chapter covers the basics of energy modeling, the second introduces the loads that go into a thermal calculation, and the final part covers energy modeling teamwork. The case studies show what architects can do, as well as hint at the depth of detail included in mechanical designs and energy models.

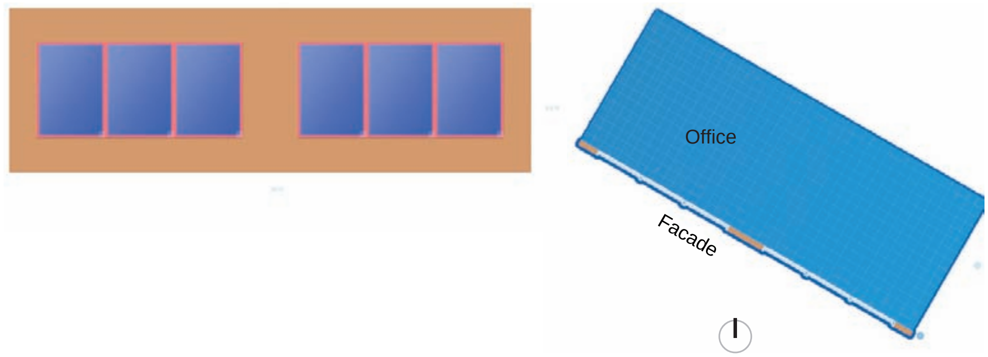
A shoebox model is used to illustrate concepts throughout this chapter, introduced in a sidebar, and explained after each section on energy modeling inputs. The model uses the free Lawrence Berkeley National Labs (LBNL) COMFEN software, which is intuitive enough for architects to use and rigorous enough to provide meaningful feedback. A single-zone southwest-facing office façade is tested in the Chicago, Illinois, climate.

ENERGY MODELING BASICS

Energy Modeling Goals

The current state of energy modeling is that many tools are available, but no single tool encompasses all necessary simulation types. There is simply too much detail to model the interactions of everything at the same time. Instead, an experienced analyst chooses the right questions to ask and sets up an energy model with the appropriate level of detail to answer them.

For this reason, there is no such thing as a "standard" energy model—each one is created to answer a different question or line of inquiry. The question is framed so that it can be answered while balancing project time, level of accuracy, and the freedom to test multiple options. The energy model is set up to



10.1

A COMFEN shoebox model will be used to illustrate the energy implications of some of the concepts covered in this chapter. The model is a 15′ deep by 38′ long bay in an office building in Chicago, Illinois, with a 58% window-to-wall ratio. Other than the façade, the walls, ceiling, and floor are adiabatic, meaning no energy transfers through them, allowing options to be tested in the shoebox that would apply to the entire building. Each input covered below has an example where that input is tested to determine its relative effects on energy use.

limit size, complexity, and thus the time necessary to answer the questions. Some examples of modeling intents are as follows:

- Determine peak heating and cooling loads, which may determine the potential for natural ventilation and some mechanical systems.
- Compare building geometry options, glazing size, and glazing locations for their effects on energy use.
- Estimate predictive Energy Use Intensity (pEUI).
- Size a mechanical system.
- Compare mechanical systems.
- Test Energy Efficiency Measures (EEMs) to determine each one's energy use savings or compare lifecycle costs.
- Validate performance of a design to comply with energy codes or receive LEED points.
- Compare actual performance to predicted performance to diagnose operational energy use problems.

THERMAL CALCULATIONS

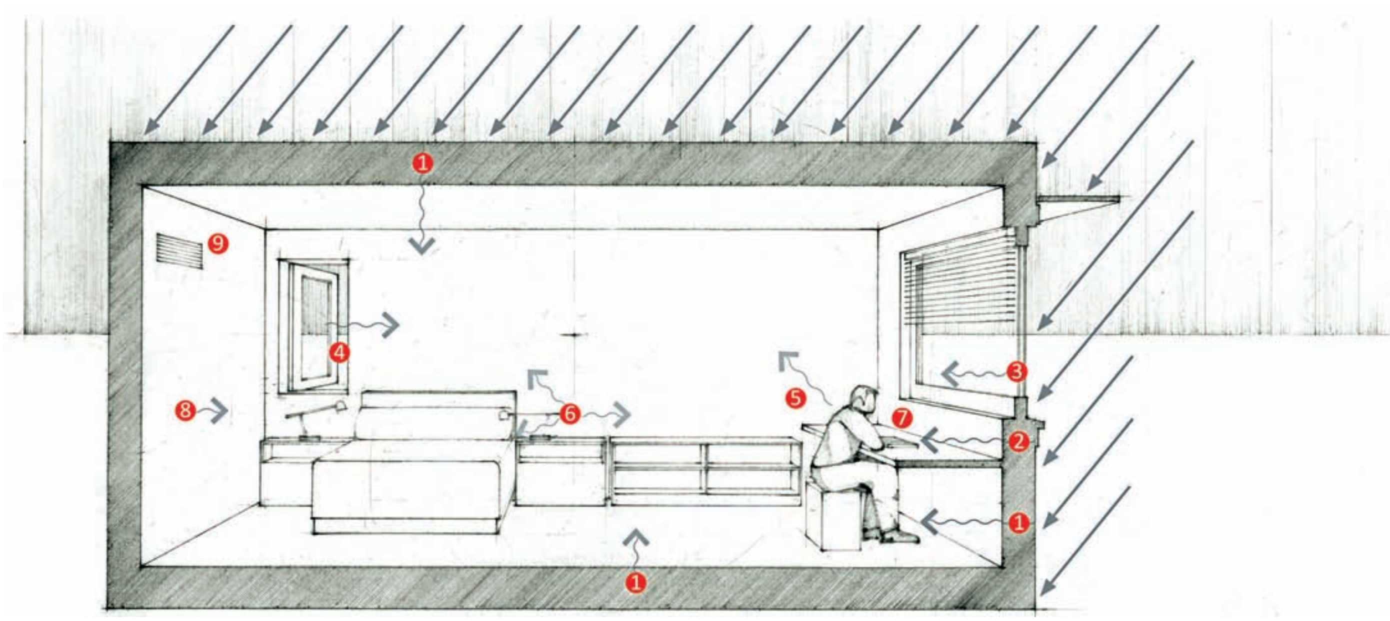
Variants of the *balance point method* are the most widely used in energy modeling simulation. This method sums heat losses and heat gains within a space, over a given period of time, resulting in an interior air temperature that is assumed to be similar to the operative temperature discussed in Chapter 3. If the air temperature is too hot, then the amount of energy required to ensure comfort in the space is called the cooling load. If the temperature is too cool, the amount of energy needed to heat it up is called the heating load. Each non-mechanical element that adds or removes heat is also called a load.

A simple version of the balance point method can be calculated using a spreadsheet with each hour of the year as an entry, as was used to model the Net Zero Energy (Living Building Challenge Certified) Bertschi School in Seattle and other small projects.

In greater detail, the balance point method is used to calculate the temperature for each surface (or multiple points on a surface), then sum the heat gains and subtract the heat losses due to convective transfer at each surface, resulting in an internal air temperature based on all surfaces. This method is perfect for simulating forced-air systems that deliver heating and cooling by controlling the air temperature. Radiant heating and cooling systems require adjustments to the method since they affect comfort without immediately affecting the air temperature.

Common inputs into an energy model, as shown in Figure 10.2, include the climate-based loads (1–4) and internal loads (5–9):

1. Conduction through the envelope.
2. Infiltration and exfiltration: air leaking through the building envelope.
3. Solar energy transmitted through glazing and opaque assemblies.
4. Fresh, outside air delivered mechanically or via natural ventilation.



10.2

A single room showing some of the inputs into an energy modeling software to determine energy use and comfort (1–9).

5 Heat given off by people, including their level of activity.
6 Electric lighting use.
7 Equipment and plug loads, such as computers, phone chargers, space heaters, refrigerators, elevators, data servers, and more.
8 Process loads: loads that are necessary for building operation but not directly attributable to other categories.
9 Heat transferred from an adjacent interior area through air or partitions.

Once the loads have been calculated for each hour (or other time-step), a system of adding and removing heat to maintain comfort is designed. This system includes heating, cooling, and any fans or pumps used to assist heat flow through the building (the HVAC system). It often includes delivery of fresh air as well.

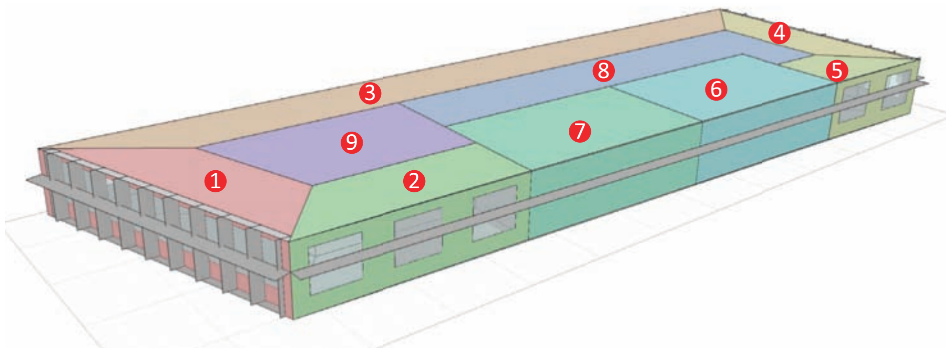
All the loads described above need to have a schedule associated with them for each hour (or other time-step) of the year. Schedules are commonly prepared for people, equipment, lighting, blinds, and others.

Many more inputs could be added to produce a finer level of detail. Energy simulation at its most detailed should contain every aspect and interaction of the physical world: climate, geometry, materiality, lighting design, mechanical, electrical and plumbing systems, thermal flow, human comfort, human behavior, and more. No energy analyst or software can yet achieve this ideal level of detail within the typical design process and fee. Instead, a model is built to answer specific questions.

Since energy modeling is such a broad field, the multitude of resources is staggering; finding the right one at the right time with the right level of detail to support the architectural process is very difficult. The best outcomes are the result of user experience, navigating the available resources to find the appropriate typical loads tables, using familiar software that has been validated, and constantly evaluating the results against the user's expected results to ensure a complete understanding of the model.

Since energy modeling is such a complex endeavor, the level of detail for energy modeling geometry and inputs in early design are guided by experience, and generally include primarliy default inputs unless better information is available.

When clients, typologies, or other project parameters provide a detailed understanding of how a building will operate, this information can be entered into the models to increase accuracy. For repeat



10.3

Thermal zones are set up for the open office west, southwest, north, east, and southeast (1–5, respectively) orientations within 15′ of the façade. Additional zones are shown for the elevator core (6) and the bathroom/service areas (7), as well as the open office not associated with an exterior wall (8–9). Since this is a single floor within a multi-floor building, it is considered a shoebox model.

Source: Modified output from Autodesk Ecotect.

clients who are aware of the requirements of known lighting levels, hours of operation and other standard procedures, existing utility data or post-occupancy analyses are useful. In most cases, though, the design team simply does not have the energy model inputs at the earliest stages. Professional energy analysts and firms often collect a library of useful inputs and post-occupancy data to increase accuracy in their models.

GEOMETRY AND THERMAL ZONES

A west-facing portion of an office building will have different solar loads at different times of the day from a south- or east-facing space or an interior space. To account for this, a building's geometry is divided into thermal zones. Heat balance calculations are completed separately for each thermal zone (1–9) in Figure 10.3.

A thermal zone is an artificial overlay on a building. Each zone encompasses an area that has relatively uniform air temperature, occupancy characteristics, and internal loads, often mirroring the spaces that will be grouped together for a mechanical distribution zone or on a thermostat. Areas that have the same orientation but different use profiles, such as a bathroom and/or an elevator, can be separated into different zones, though at the earliest stages of design this is not necessary.

Each attribute of each thermal zone needs to be understood and agreed upon by the project team. For example, a school that is modeled for energy use based on 20 students per classroom will perform differently with 40 children per classroom; or one that is modeled with 20 computers at 300 W each will return different results than one modeled with no computers. Since the actual numbers cannot be known, averaged numbers are often used in early energy modeling.

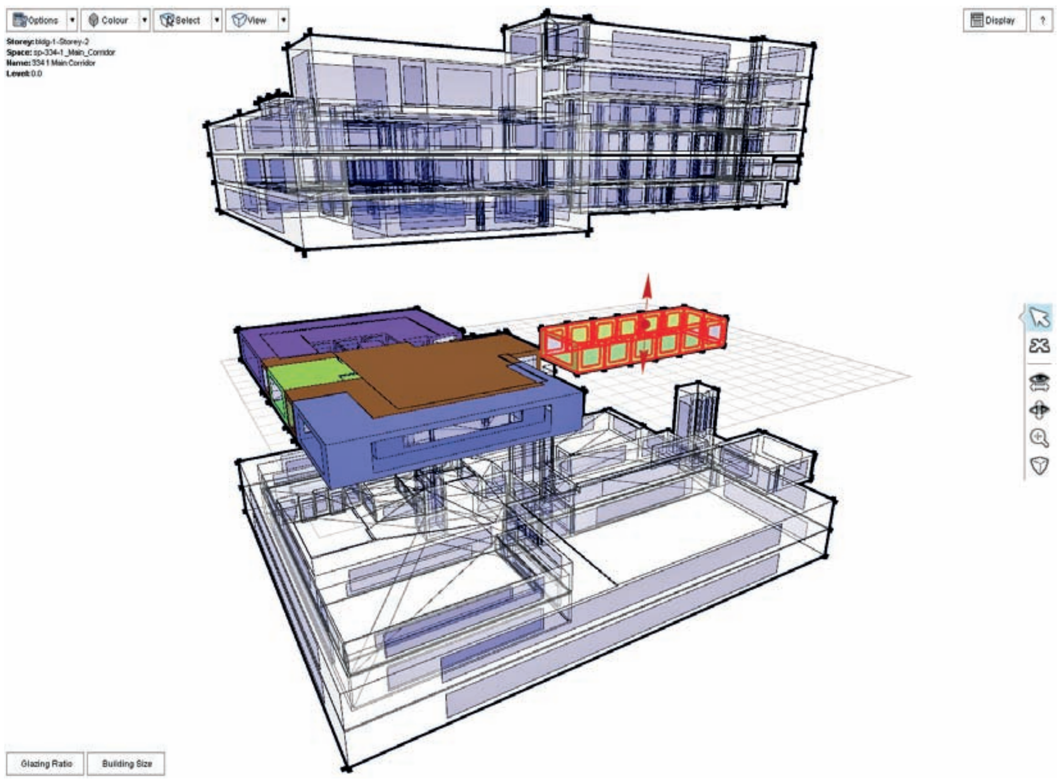
Zones are not necessarily individual rooms; they are typically grouped by orientation, distance from the façade, and use. Since more zones increase the run-time of a simulation, the energy modeler needs to exercise judgment when determining how to divide a space into thermal zones.

Per ASHRAE Standard 90.1, the first 15′ inside each façade orientation is grouped into a thermal zone, with a separate thermal zone for "interior" areas farther from the façade. This allows the software to separately calculate how the area at the perimeter interacts with the climate, heated by solar irradiation or cooled by conduction through the façade.

In preparing a geometric model for energy simulation, each zone needs to be a continuous, "air-tight" enclosure for software to work properly. Adjacent zones may have their touching walls set to a "void" or "air-wall" material to allow free air exchange between the zones without breaking the "air-tight" rule. Creating air-tight thermal zones in design-oriented 3D modeling programs is a challenge, so automated software assists in detecting good locations for thermal zones and filling in any gaps to make them airtight.

SHOEBOX MODELS

A single-zone model, or one with only a few zones, is often referred to as a shoebox model. Architects and many professional energy analysts use shoebox modeling, since most whole building energy



10.4

Exploded model showing a single thermal zone (in red) that is being analyzed as a shoebox model. Adiabatic walls are located adjacent to other internal spaces to keep heat from flowing through them. In this case, adiabatic walls are located on the top, bottom, and left side of the zone.

Source: Courtesy of Andrew Marsh.

simulations (WBES) require a mechanical system design. Architects will generally use automated versions of shoebox modeling, where the software uses reasonable default inputs.

In order to study a portion of a building, the rest of the building needs to be excluded from an energy model. This is done by placing adiabatic walls (which have the imaginary property of transferring no heat) where the shoebox model touches other conditioned spaces. This limits heat transfer to those façades that interact with the outdoors.

Shoebox models allow the investigation of repetitive elements, such as hotel rooms with similar orientations, or floors of a high-rise building as in the above example. They also allow a project team to investigate a specific portion of a building to improve local comfort or energy use.

ENERGY MODELING LOADS

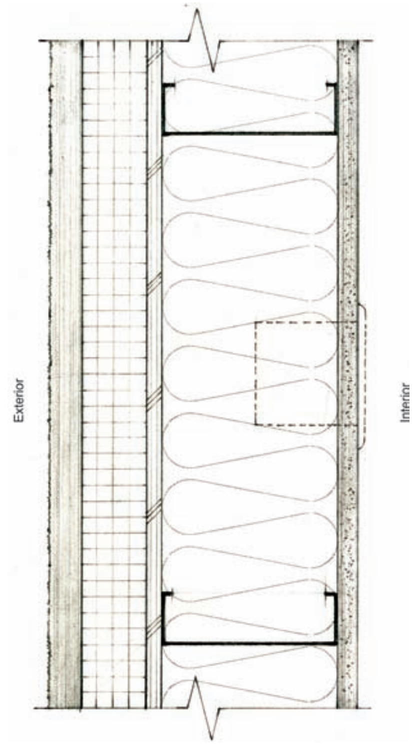
Geometry

When designing low-energy buildings, architects control some of the most important aspects of passive design: the geometric expression of massing and program, glazing size, and glazing location. These affect nearly every load. Historically, most energy models have been used to test mechanical systems and non-geometric inputs since the models are done at the back end of design and often housed within mechanical engineering firms; however, as architects employ energy modeling in early design, geometries can be reasonably tested to determine an optimal design for energy use.

CLIMATE-BASED LOADS

Solar Load

Solar energy transmitted through glazing was discussed in detail in Chapter 6. In many climates the solar load is the major contributor to peak cooling loads, so controlling it through glazing orientation, size, and shading can be crucial in low-energy design.



10.5

Summing the R-values of the layers yields an assembly R-value:

0.68 inside air film

0.45 interior wallboard

7.10 R-19 batt insulation between metal studs @16″ o.c.

0.63 exterior sheathing—0.5″

7.50 extruded polystyrene rigid insulation –1.5″

0.80 exterior cedar siding, lapped

0.17 outside air film

17.33 = Total R-value

(.058 = Total U-value)

Conduction Load

The conductivity of a wall or window, called the U-value, determines the speed at which heat transfers between the inside and outside. The U-value is assigned to various materials and assemblies based on lab tests. While specifically referred to as conductivity, the tests include all forms of heat transfer: conduction, convection, and radiation. The inverse of the U-value, the R-value, refers to thermal resistance.

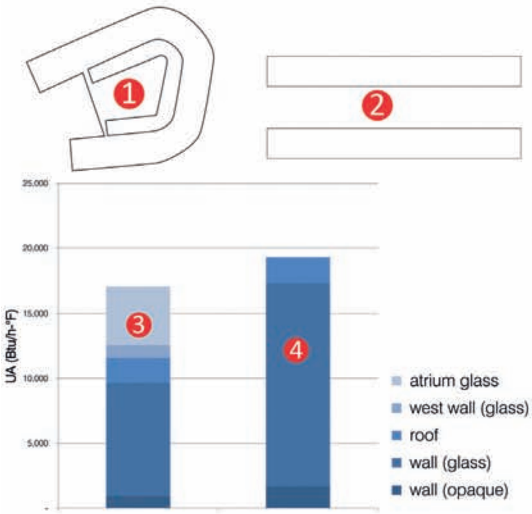
Building materials are layered to form wall or window assemblies using the R-value. The calculation of an assembly thermal resistance can be done by summing the R-values of each material layer, or, more accurately, by using a program such as THERM. The R-value can refer to either the total insulation value of an assembly or material, or the insulation properties of a material per inch of thickness.

A wall assembly is calculated above—note that 1.5″ of continuous rigid insulation (R-7.5 total) provides more thermal resistance than the metal studs with R-19 batt insulation. Metal studs are highly conductive, so they provide a thermal bridge for heat to bypass the insulation, reducing the effectiveness of the studs and insulation to R-7.1 total.

While radiant barriers have a negligible R-value themselves, they can reduce radiant heat transfer across an air gap as small as 1/8″, increasing an assembly insulation value. Their effect on the R-value is tricky to calculate, so often an entire assembly is tested to determine the increased thermal resistance.

Energy loss or gain through an opaque wall is calculated by multiplying the difference between the outdoor and indoor temperatures by the U-value and the amount of wall area of the assembly. The UA method (multiplying the U-value by the area) produces a number used in energy codes for insulation trade-offs. For example, a higher glazing percentage can be balanced by a better glazing or opaque U-value. The UA for each assembly is calculated and then all UAs are summed to produce a value for an entire building. This method does not take into account solar irradiation, thermal lag, or orientation, but has the right balance between ease and accuracy for widespread use.

Ecotope Engineers have found that recommending a budget of .1 UA/ft^2 for medium-sized projects gives design teams a flexible goal that will help produce a low-energy building in the Seattle climate. For this goal, UA is summed for all envelope assemblies and then divided by the floor area.



	Fed Center South (1)			Baseline (2)	
	U (Btu/h-ft^2-°)	SF	UA	SF	UA
wall (opaque)	0.05	17,591	932	31,617	1,676
wall (glass)	0.33	26,386	8,707	47,426	15,650
roof	0.03	58,059	1,941	58,985	1,972
west wall (glass)	0.33	3,006	992	-	19,298
atrium glass	0.38	11,889	4,518	-	38,595
Total			17,090		77,191

10.6

A simple trade-off calculation during the early phases of a project compares energy flow through all façades using the UA method. The U-shaped design (1) with enclosed atrium is compared to a similar floor plate width and overall building size in a bar (2) building. Increased heat loss due to the vertical glazing for the atrium (3) is more than offset by reduced heat loss due to a reduced exterior glazed area (4). U-value assumptions for each wall and glazing type are included.

Source: Courtesy of ZGF Architects.

Thermal storage within an exterior wall assembly delays conduction loads through the building skin in addition to providing thermal mass that tempers the interior temperatures. The effects of thermal mass within an exterior wall can quickly be estimated through the use of the *ASHRAE Handbook*'s Radiant Time Series method, which approximates time delay within different assemblies in terms of "Conduction Time Factors." For example, a 12″ exterior concrete wall with insulation spreads out daily heat gain or loss nearly evenly over the next 24-hour period. By contrast, an insulated curtain wall spandrel transfers 96% of the conduction heat to the interior within 3 hours.

While there are exceptions, more insulation is often one of the most cost-effective, low-technology design moves that can reduce energy consumption. Increasing insulation levels tends to lead to smaller mechanical plant and ductwork sizes, lower heating and cooling loads, and generally increased comfort. In buildings with a high glazing percentage achieving a high insulation value requires triple or quadruple glazing, which are often prohibitively expensive.

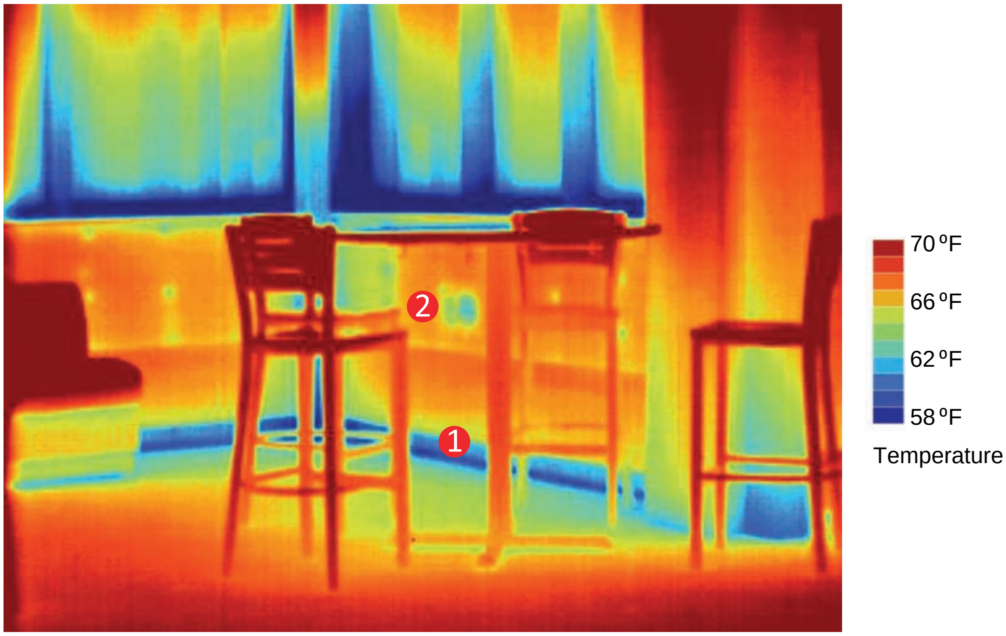
In this shoebox model example, for the opaque walls, COMFEN defaulted to 16″ o.c. 2 x 4 wood stud construction with R-13 insulation and R3.8 continuous insulation outside the sheathing, with a total insulation value of R-18. This was modified to a 6″ metal stud wall with R-19 insulation and 7.5″ of extruded polystyrene insulation outside the sheathing, with a resulting R-value of 17.33. Changing from this to a highly insulated envelope (R-29) yielded only half a percent energy savings due to the high (58%) glazing percentage and modest insulation value of the glazing.

The baseline glazing type used was a low-SHGC (Tvis = .37, SHGC = .24, U-value = .25). This was tested against one with higher SHGC (Tvis =.70, SHGC =.47 and U-value = .245), resulting in 20% higher annual energy use. Lowering the glazing percentage from 58% to 47% yielded a 6% annual energy savings, but would likely have additional effects on energy use that could only be determined through a full energy model.

Thermal Bridging

When insulation is penetrated by conductive materials, especially metals, the effective thermal resistance of the assembly is reduced. Even though low-energy building design involves reducing heat transfer through thermal bridging, most energy models do not account for this effect. Instead, a well-researched U-value that approximates thermal bridging is used in an energy model.

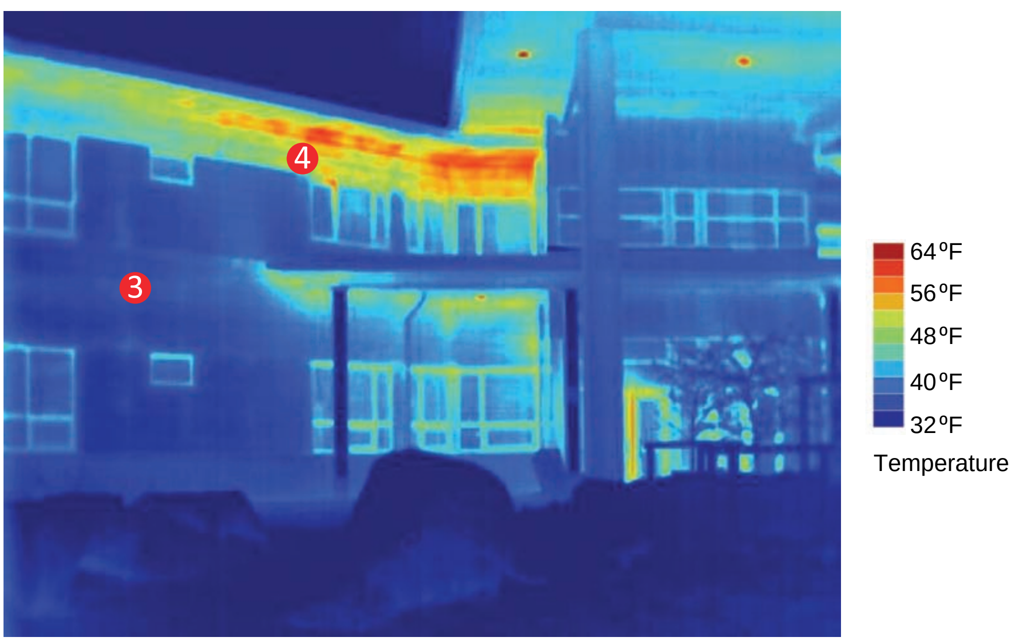
Thermal bridge calculations can be done with THERM or other software, illustrated in Case Study 10.5. Consideration of the resulting conduction value is incorporated into Passivhaus software, for instance.



10.7

Thermal image showing the relative temperatures of interior surfaces. This type of image can be used to locate air leaks and thermal bridging. The connection between the wall and floor (1) allows a thermal bridge or air leakage from the outside. Air often leaks through the drywall penetration for the electrical box (2). The blue area at the base of the window shows cold air circulating due to conduction through the window, a typical occurrence.

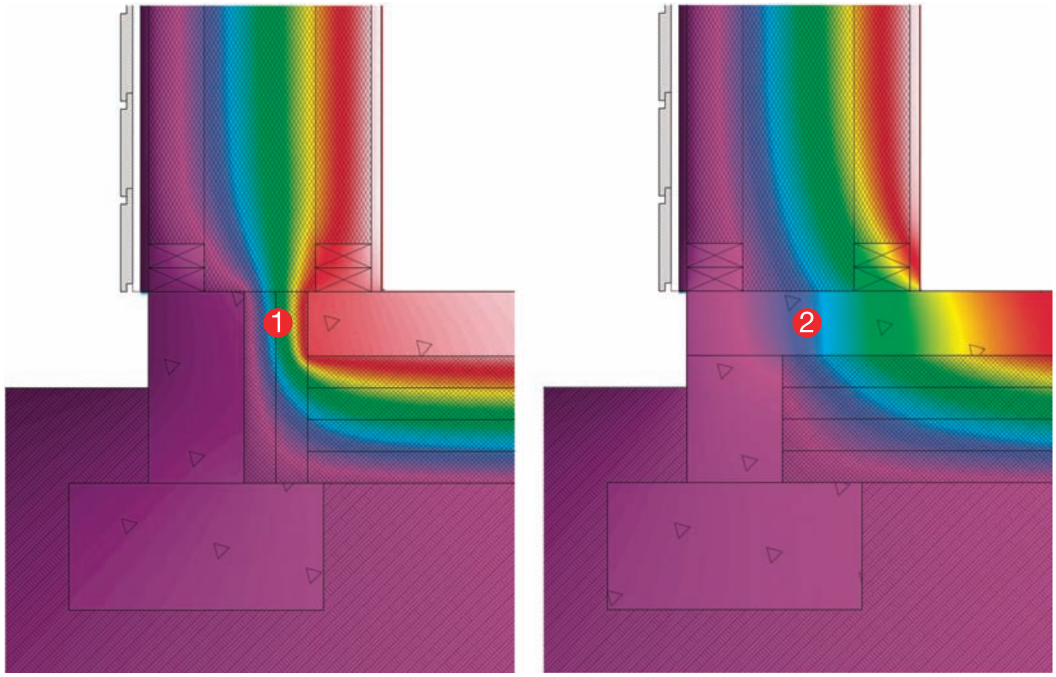
Source: Courtesy of Neudorfer Engineers.



10.8

The typical wall assembly (3) shows normal thermal bridging through the studs. The energy leakage at the lower roof (4) shows the effects of a series of cantilevered C-channels that penetrate the wall to support the exterior overhangs. With the building under slightly positive pressure, warm air passes through the center of the C-channel and out through the metal siding and soffit material.

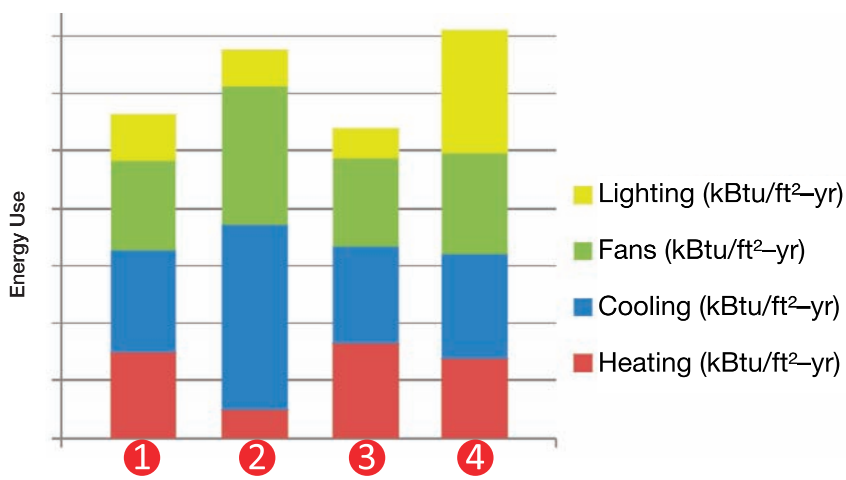
Source: Courtesy of Neudorfer Engineers.



10.9

Passivhaus training includes methods of using THERM software to look at thermal bridging through assemblies. This detail shows a highly insulating material (1) at the critical intersection of the wall and floor, preventing the usual conductive heat loss (2) if a continuous slab were used. For a building otherwise designed to Passivhaus standards, the left detail would reduce heating requirements around 16%. False colors show isothermic temperature bands.

Source: Courtesy of Brute Force Collaborative.



10.10

COMFEN's results from the shoebox model example in Chicago. The baseline (1) is compared to using clearer glass with the same U-value but a higher Tvis and SHGC (2), which increases energy use by 20%. Lowering the lighting power density (LPD) of the perimeter zone improves performance by around 5% (3), assuming the blinds are actively raised and lowered based on glare. If the blinds are always left down to block glare (4), energy use increases 26% above the baseline.

In many cases, thermal bridges occur due to a steel or concrete structure that spans from a conditioned space to an unconditioned space. This happens at cantilevered balconies, eaves, canopies, and in many conditions in most buildings. Metal framing studs also provide thermal bridges, reducing the thermal resistance of an insulated wall assembly by nearly half.

For a Callison project in Vail, Colorado, the contractor revealed their poor experiences with cantilevered concrete decks. Since the decks provided a thermal bridge between the interior and exterior, during cold periods, condensation appeared on the interior floor near the decks. The team chose to include a thermally broken structure for balconies.

Sol-air Loads

Sol-air loads are created by solar energy falling on the building façades, heating them up, and changing the quantity of heat transferred through them. During cold periods, it reduces conductive heat loss, during hot periods, sol-air loads increase heat conducted through the façade. Energy modeling software creates a synthetic sol-air temperature to mimic this effect, which is used instead of actual exterior temperatures for hourly conduction loads. In lightweight buildings, sol-air loads through the opaque façades can significantly affect peak loads and indoor comfort.

One example of the importance of sol-air temperatures is the green building movement's focus on low-albedo (high-reflectance) roofing materials to reduce sol-air temperature gains in the summer in most climates. The color black, typically used for flat roof membranes, absorbs three to five times more solar energy than reflective white roofs, transferring much of this energy to the building interior. White roofs absorb less sol-air gains, decreasing peak and annual cooling loads.

Infiltration/Exfiltration Loads

All buildings leak air to some extent. Infiltration, which specifically refers to air leaking into a building, is also a general term that can refer to exfiltration, or air leaking out of a building. Infiltration introduces additional heating or cooling loads based on the outdoor air temperature and the rate of leakage. Unintentional air leakage can also deposit moisture within wall assemblies which can lead to mold and early assembly failure.

Infiltration happens in all buildings, driven by pressure differentials between the inside and outside of a building, as well as the permeability or gaps between building materials. The pressure differential can be due to wind, a mechanical system maintaining a slightly positive or negative pressure, or the stack effect. The stack effect refers to a large positive pressure near the top of tall buildings that pushes air out, and a resulting negative pressure at the bottom of the building that sucks air in. In most building simulations, infiltration is a roughly estimated factor based on expected detail and construction quality.

A "blower door" test has been done for many single-family houses and Passivhaus buildings to quantify and locate air leakage. Building codes are beginning to require larger buildings to pass a similar test; as they do so, data will be collected that can inform the next generation of energy modeling.

A blower door test usually involves pressurizing or depressurizing a building to 50 or 75 Pascals, and then measuring the volume of additional air that is needed to maintain the pressure within the building. At this high level of pressure, codes currently target from .25 to .40 cubic feet per minute per square foot of façade as a maximum (cfm/ft^2) for a whole building test. At normal pressures and moderate wind speeds, infiltration is in the order of .10 to .60 cfm/ft^2 of exterior wall, or 1–3 complete air changes per hour (ACH), depending upon the quality of the architectural details and construction practices and the expected pressurization due to the mechanical system.

In the shoebox model example, the COMFEN model defaulted to an infiltration rate and schedule for a typical office, with higher losses during unoccupied times. This was not modified.

Fresh Air Loads

Human comfort and health depend on constantly supplying fresh air so that indoor oxygen levels mimic outdoor conditions. A hundred years ago fresh air was supplied entirely by infiltration and operable

10.11 and 10.12

Testing air leakage (infiltration) requires pressurizing or de-pressurizing a building. For residential projects, such as this Passivhaus, a blower door test is performed by replacing a door with a large fan and then sealing the opening with an airtight sheet. A gauge then measures the air leakage. Poorly sealed areas can be found by using a tracer gas or with a thermal imaging camera on a cold or hot day.

Source: Courtesy of Eco-Cor.

windows. Infiltration has been reduced through tighter construction practices in the twenty-first century, making fresh air delivery more important.

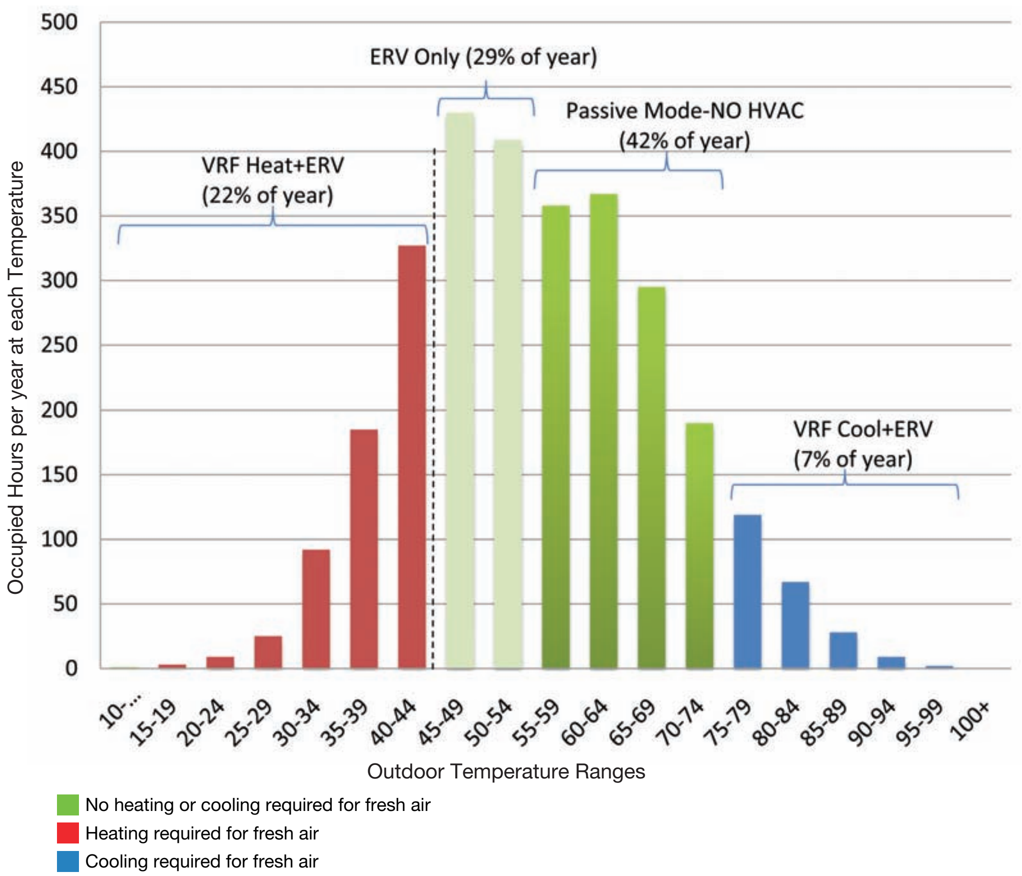
Standards generally require a minimum quantity of fresh air per volume of interior space to remove pollutants such as carcinogens and dust, and additional fresh air per person or based on CO_2 levels within each space. Fresh air code requirements may total 5–20 cubic feet per minute (cfm) per person in office occupancies, for example. ASHRAE Standard 62.1 contains standard ventilation rates for various typologies and situations. These are combined with the occupancy schedule to determine hourly fresh air supply rates in an energy model.

Since fresh air is taken in at outdoor temperatures, energy is used to heat or cool the air and for fans to continually supply and remove exhaust air. Fresh air in modern buildings is supplied in two main ways—through ductwork using fans to move air, or using natural ventilation. Naturally ventilated buildings use the flow of unfiltered outdoor air to maintain healthy oxygen levels, and this air is often also used to cool the spaces as well. Natural ventilation is discussed in Chapter 9.

Most buildings with forced air mechanical systems simultaneously deliver fresh air along with heating or cooling. Since fresh air often needs to be heated or cooled, re-circulated air is mixed with a minimum of fresh air to reduce energy use, pitting air quality against energy efficiency. Low-energy buildings often de-couple fresh air delivery from heating and cooling. They use trickle vents or operable windows to supply fresh air when outdoor conditions are within certain temperature ranges, sometimes with a backup system to supply minimum ventilation air during more extreme periods.

Heat recovery ventilators (HRVs) and energy recovery ventilators (ERVs) transfer energy from the exhaust air to incoming fresh air. HRVs transfer only sensible (temperature) heat, while ERVs transfer some latent heat (humidity) as well. The exhaust and supply air do not touch, though the supply and return ductwork needs to be adjacent to connect to an HRV or ERV unless a thermal loop connects them.

In the shoebox model example, the COMFEN model defaulted to 21.2 cfm/person based on the office occupancy, which was modified to 17 cfm/person based on the ASHRAE 62.1–2007 minimum. No HRV or ERV option is available in COMFEN.



10.13

When temperatures are sorted into "bins," the number of operating hours at each temperature can be seen, which affects the conduction and fresh air loads of a building. A building with little insulation requires fresh air to be heated when outside temperatures are below a balance point, around 65°F. The number of hours where no heating or cooling is required can be increased through insulation and energy recovery. In this case, the building does not require heating or cooling for 70% of occupied hours. More detail can be found in Case Study 10.5.

Source: Courtesy of Ecotope Engineers.

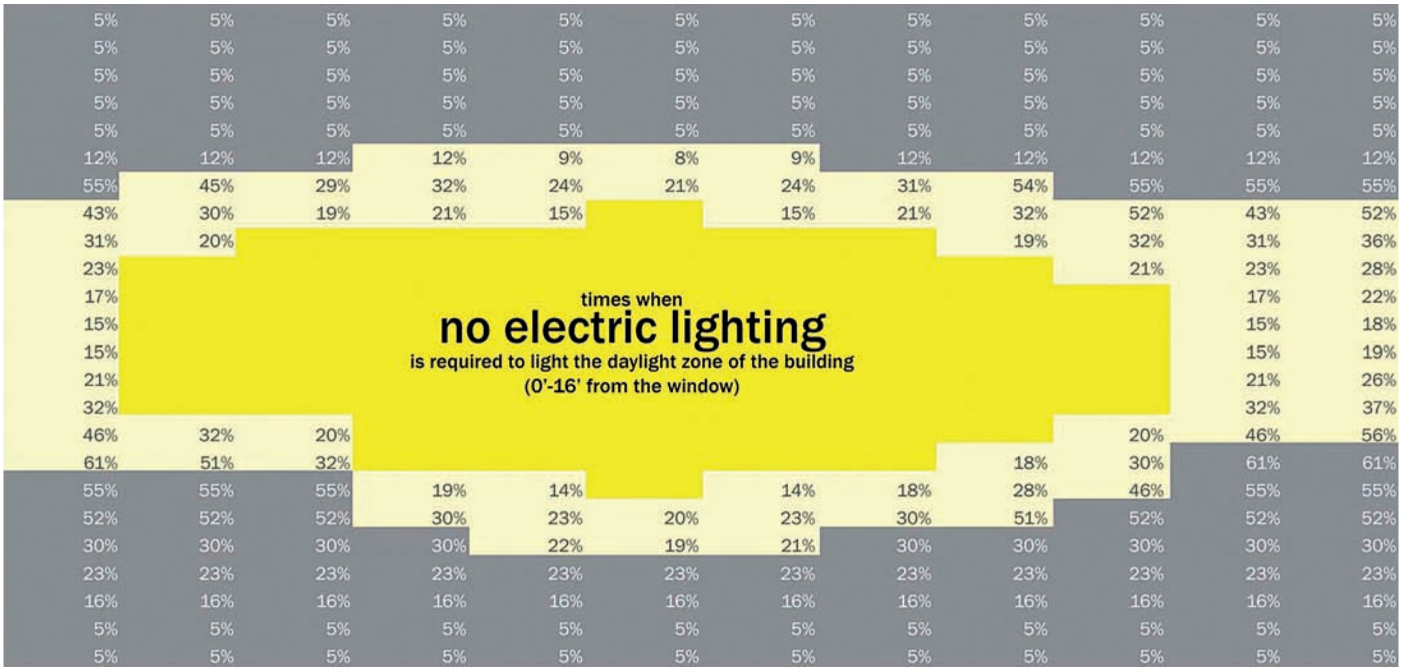
INTERNAL LOADS

Internal loads refer to heat sources within a building that are not part of the HVAC system, including people, electric lighting, and waste heat from equipment. Some occupancy types with a high density of these elements, such as office and auditoriums, require cooling even during cold seasons. They are sometimes referred to as "internal load-dominated buildings," since their energy use is more dependent on internal loads than on climate-based loads. Internal loads are generally decreasing as more efficient technology for lighting and equipment generate less waste heat. With higher insulation levels and less infiltration, though, internal loads become a larger factor.

Any electricity-using internal load is a double load during warm seasons: a computer, for example, consumes a number of Watts to function, and releases a similar amount of Watts as "waste" heat that needs to be removed to maintain comfort. While waste heat can be beneficial during cold periods, the same quantity of heat could be delivered with a lower carbon footprint as an intentional heat source.

People

People shed heat constantly to maintain a constant core temperature. Sitting people generate between 330 and 475 Btu/hour of heat. Standing and walking people generate around 450–550 Btu/hr, people engaged in athletics can add from 800–2000 Btu/hr. People contribute to both the sensible heating (air temperature) and latent heating (the energy embodied in humidity) of a space. See ASHRAE (2005) *Handbook of Fundamentals*, 30.4 Table of Heat given off by people.



10.14

Lighting use factor schedule for the electric lighting in the perimeter zone of the Edith Green–Wendell Wyatt office building in Portland, Oregon. See Case Study 7.1.

Source: Courtesy of SERA Architects.

In early design, the actual number of occupants is often not known, so reasonable estimates are made: 150–200 ft^2/occupant for office, the number of bedrooms plus 1 for residential, around 60% room occupancy for hotels, or a fraction of the number of fixed seats for assembly.

In the shoebox model example, for the COMFEN study, the anticipated occupancy of around 200 ft^2 per person within the 570 ft^2 zone meant approximately three people are typically in the zone during peak occupancy, assigned a sedentary metabolic rate. If the mechanical system was designed for six people to be in this zone instead, energy use would increase around 20% due to the increase in fresh air requirements.

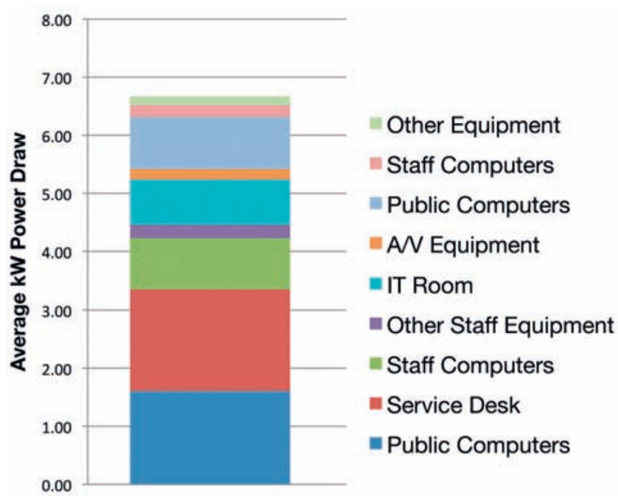
Lighting Loads

Lighting power density (LPD) measures the energy required, in Watts/ft^2, if all lights in an area are on. Energy codes limit the LPD to control the maximum amount of energy used by all lighting installed within a building. For an energy model, a schedule containing the amount of electricity used for electric lighting at each hour needs to be estimated. The resulting lighting use factor (LUF) is based on the ratio of the amount of lighting energy being used to the amount of lighting energy installed. Lights dimmed to 50% will have a LUF of approximately .60, or approximately 60% of the installed LPD. Task lights are considered plug loads, so they are often excluded from the LPD and LUF.

While the LUF will have a schedule similar to occupancy in many spaces, within the daylight zone the LUF will fluctuate throughout each day and year based on daylight levels. A daylight zone is any area near windows or skylights that have lights on a photosensor and dimmer in response to daylight levels.

An annual schedule needs to be created for dimmed and off lights based both on daylight levels and glare potential. The most difficult part of creating this schedule is estimating when blinds and shades will be deployed, which can be informed by glare studies discussed in Chapter 8.

To quantify lighting and cooling energy savings, dimming capabilities also need to be known. Advanced dimming systems can dim all the way to "off," but most dim from 100% down to 10% or 20% at the lowest "on" setting. Other lights have multiple ballasts, where one ballast can be turned off, reducing electric lighting levels in response to daylight.



10.15

Plug load analysis for the West Berkeley Library was based on surveys of the existing library, and included over 90 individual plug loads. Since the project targeted Net Zero Energy and reduced all other loads, plug loads will account for around 40% of the project's energy use. The chart breaks down plug loads into attributable uses; computers make up most of this load.

Source: Courtesy of HED Architects.

Different energy modeling engines vary in their ability to assess how daylighting will affect lighting energy use within a space. The energy analyst may need to manually input the lighting use factor into a schedule or calibrate the results of the energy model with more accurate daylighting and glare results as discussed in Case Study 10.7.

In the shoebox model example, the lighting power density defaulted to 1 W/ft^2, consistent with the 2009 International Energy Conservation Code (IECC). If the lighting power density was reduced to .65 W/ft^2 by using LED fixtures and lamps, lighting and cooling energy use would both decrease, saving 5% of annual energy use. The LED fixtures and lamps would produce more energy savings if blinds were simulated to be in the down position more often, or in a zone with less daylight access.

Process Loads, Including Plug Loads

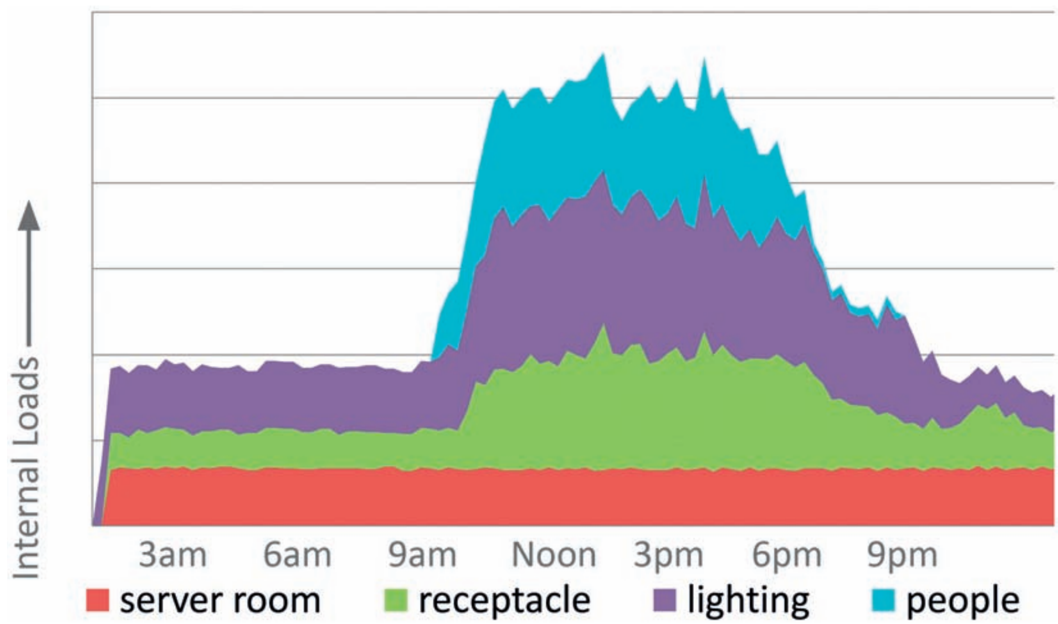
Process loads include electric uses that are not part of heating, cooling, or lighting systems, though there is not widespread agreement about a specific definition of process loads. They include elevators, servers, computers, copiers, refrigerators, and many more items. Process and plug loads are usually referred to as a load factor and estimated in Watts/ft^2 for an energy model.

Plug loads generally include anything plugged into wall outlets. While plug loads account for around 19% of building energy use nationally, regulating plug loads is one of the biggest challenges in low-energy and NZE buildings, where they may account for over half of annual energy use.

A schedule of plug loads created for an energy model is often directly related to occupancy, since the use of electronics is generally higher when people are present. Plug loads are difficult to anticipate and control, since electronics are continually being invented or improved. In addition, the rated wattage of electronics does not indicate their normal power usage, especially with different modes—on, sleeping, power saving, off, and others. Energy Star-rated electronics have been measured to use 50% less energy than typical equipment, though continual advances in electronics mean that Energy Star equipment from 5 years ago may be considered wasteful today.

The unknowns associated with plug loads can be mitigated by engaging building occupants, as described in Chapter 3, Comfort and Controls. Users who are aware of their energy use tend to reduce their energy use. Assigning an energy use for plug loads per person, instead of per ft^2, can help a design team understand the implications of various electronics.

As an example, the Bullitt Center project team did studies during the design process to reduce each workstation from 250 W/person to 42 W/person using remote workstations, energy-saving displays, and a central server as a necessary step to achieve Net Zero Energy as shown in Case Study 10.7. When power bills from the Rice Fergus Miller offices were evaluated for actual performance, the EUI was much



10.16

Measured internal load profile from a single day at the Rice Fergus Miller offices. Lighting controls reduced lighting energy use from the installed lighting power density of .59 W/ft^2 to an average use of .32 W/ft^2. Powering computers off at night eliminates most of the plug loads, while the server runs all night.

Source: Courtesy of Rice Fergus Miller and Ecotope.

higher than anticipated since employees were not turning off their computers at night. Once this became standard practice, the building met its target EUI of 19, see Case Study 10.5.

In the shoebox model example, default plug loads were at .75 W/ft^2 based on an average usage from surveys. A reduction in just the plug loads to .5W/ft^2 resulted in a 1% energy savings, while if a small server rack raised the equipment load to 1.5 W/ft^2, energy use would increase 3%. Energy savings from these measures would be much higher if this were an internal zone instead of a perimeter zone with significant heat loss through the glazing.

SCHEDULES

In all types of spaces people come and go, turn on and off lights and computers and need fresh air delivered. Setting up an energy model requires that an hour-by-hour schedule is associated with each element covered in this for each space type. This includes the number of people within a thermal zone for each hour of the day, their comfort requirements, their electronics, and their habits. While it is impossible to predict behavior, the probability of various behaviors are incorporated into standards used for energy modeling. For climate-based loads, hourly weather conditions are contained within the weather file. Even the leaves on trees that provide shading and glare control can be put into a schedule, as in Case Study 8.8.

A schedule is usually set up for typical weekdays, weekends and unusual but predictable events. For example, occupancies are amended at shopping malls and retailers near holidays, hotels during travel or convention seasons, and university housing during breaks.

A schedule usually contains a percentage of the maximum value for each hour. For example, at 7 a.m. in an office, 40% of the staff may be in, while at 10 a.m., 100% may be there. Assigning percentages allows the total number to be adjusted without having to redo the schedule.

A schedule contains upper and lower thermostat set points for each hour of the day, which determines the conditions under which the mechanical or natural ventilation system will add or remove heat from a space. The set point during occupied hours are based on the comfort conditions discussed in Chapter 3, while a wider variation of temperatures is usually acceptable at night and when buildings are expected to be unoccupied.

Simulating user behavior to create a schedule for shades and blinds is important as they are part of the shading, mechanical, daylighting, and glare control systems; it is also very tricky. Occupants may

Equipment Energy Use

		2		4		6		8		10		Noon		2		4		6		8		10		12
Weekday	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.9	0.9	0.9	0.9	0.9	0.8	0.9	0.9	0.9	0.9	0.5	0.4	0.4	0.4	0.4	0.4	0.4
Saturday	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.5	0.5	0.4	0.4	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Sunday, Holiday	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

Occupancy

		2		4		6		8		10		Noon		2		4		6		8		10		12
Weekday	0.0	0.0	0.0	0.0	0.1	0.2	0.3	1.0	1.0	1.0	1.0	1.0	0.5	1.0	1.0	1.0	1.0	0.3	0.1	0.1	0.1	0.1	0.1	0.1
Saturday	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.3	0.3	0.3	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0
Sunday, Holiday	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

10.17

Equipment energy use and occupancy schedules. The number for each hour shows the fraction of the total equipment and total occupancy for that period. For instance, if the maximum number of occupants is 40, there would be 36 occupants at 10 a.m. on a weekday and 12 at 10 a.m. on a Saturday. Note that 40% of the equipment is assumed to be left on all night on weeknights, with 30% left on all weekend. Significant energy reductions can be realized simply by changing the operational characteristics and habits of occupants. Note that over 50% of Equipment energy use is assumed to be outside of the time when people are in the building.

be seated at optimal or worst-case locations for glare, blinds and shades can be adjusted to any height, and users may be active or passive in their deployment of blinds and shades. For these reasons, blinds schedules rely on statistical probabilities based on research. In some cases, the software locates a small number of glare sensors within a space, and uses glare algorithms to simulate manual operation of blinds.

EnergyPlus, for example, includes 19 blinds-deployment settings based on: glare (using the Daylight Glare Index), internal temperature, outside temperature, solar irradiation, and other factors. The energy analyst needs to input when blinds or shades will reasonably be deployed so that the software can estimate their effect on electric lighting.

in the shoebox energy example, the COMFEN model automatically contains schedules for infiltration, lighting, occupancy, equipment, heating and cooling set points, and more. These can be edited using a text editor, but they were deemed to be adequate for an early analysis. Schedules for the interior operable venetian blinds were initially set for always being down as a worst case, but were modified to be deployed only when glare was high, with a 4% decrease in energy use due to a lower heating demand.

HEATING, VENTILATION, AND AIR CONDITIONING SYSTEMS

Nearly every energy model requires the user to select a mechanical system, also called a heating, ventilation, and air conditioning (HVAC) system or a comfort system. While architects' goals with early design simulation and energy modeling are generally to reduce loads passively, the mechanical system selection and design can have a large impact on resulting energy use, and each has its own advantages and disadvantages.

An HVAC system generally contains a *source* of heating and cooling, a *distribution system* for the heat or cooling, and a method of supplying *fresh air*. In commercial buildings, a boiler and chiller supply the heating and cooling, fans and ductwork are used to supply heating and cooling to spaces, and fresh air is mixed with re-circulated air and supplied via the ductwork.

Many low-energy buildings are designed to meet comfort standards without using the mechanical system for heating and cooling during milder portions of the year. When they do use mechanical heating or cooling, the design separates heating and cooling from fresh air supply. They use water or refrigerants to distribute heat through a building using radiant panels.

An energy model without a mechanical system results in a "free-run" interior temperature. This is useful when a design looks to provide comfort without using the mechanical system during part of the year, or when a heating or cooling system may be eliminated entirely. This type of analysis usually results in a number of hours in an average year where conditions may not be within the comfort range determined for the project. The team can then determine what additional measures need to be taken to ensure comfort. Architects can also use this type of analysis to compare early design options to reduce overall heating and cooling loads, knowing that this will reduce energy use regardless of the final HVAC system selection and design.

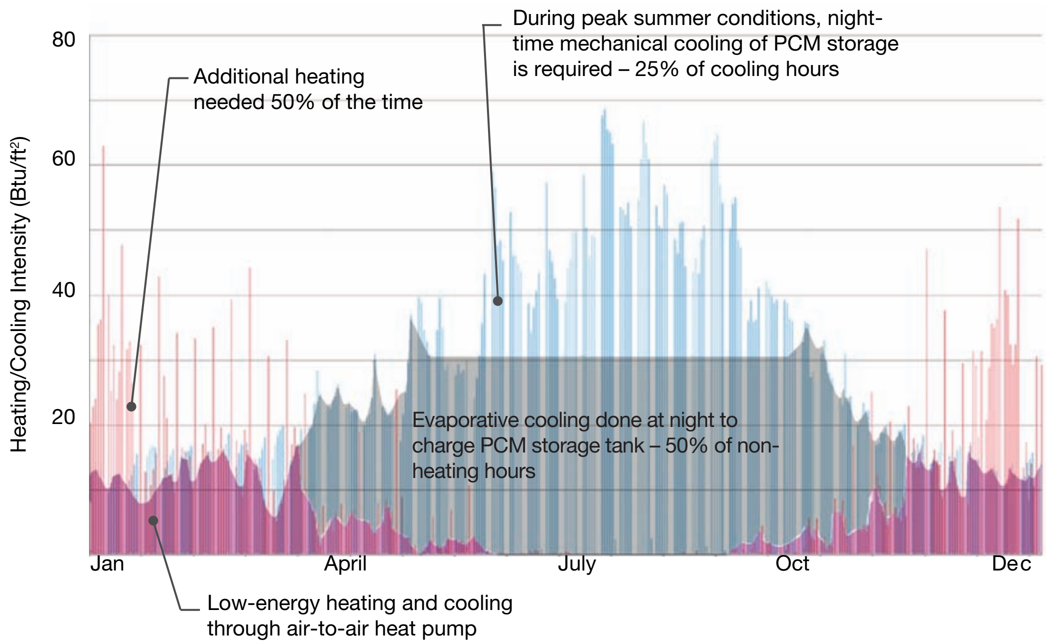
Architects doing shoebox analysis early in design are encouraged to consult a mechanical designer to determine the best type of system to select within a model. Most automated software will then use

10.18 and 10.19

Phase change materials (PCMs) contained in a rooftop tank are used for thermal storage, integrated into the mechanical system of the Federal Center South in Seattle, WA. PCMs may improve both heating and cooling efficiency: when melted (liquid), they are a source of heat during morning warm up and, when frozen (solid), they are a source of cooling during the day. Warm water that has absorbed loads from space cooling melts the PCMs and is returned as cold water to the building's chilled beam system.

The diagram shows heating and cooling loads for each day of the year, with red for heating loads and blue for cooling loads. Freezing the PCMs can be done at night to avoid peak electricity charges and peak grid demand and reduce energy use. Freezing PCMs also occurs during morning warm up when heat is extracted from the PCMs. PCMs are covered in Chapter 6.

Source: Courtesy of WSP Flack + Kurtz. Photo © RC Bowlin.



averaged HVAC energy consumption data for buildings with the chosen type of mechanical system. In some cases, the software will attempt to do a reasonable mechanical layout based on the system chosen.

Both of these are less accurate than having a building-specific HVAC design. Having a specific mechanical design is especially important when advanced systems or unusual geometries are pursued.

In the shoebox energy model, COMFEN only includes a single mechanical system—a Packaged Single-zone system. This makes the HVAC choice easy, if limiting, for architects.

ENERGY MODELING TEAMWORK

Who Does Energy Modeling?

The most effective way to reduce energy use and achieve the project team's goals for a reasonable cost is to utilize an integrated design process, where the architect has access to in-house modeling, and the mechanical engineer and energy analyst are able to provide expertise and simulation at the earliest phase of design.

In current practice, however, energy modeling is most often performed within a mechanical engineering firm with a completed or nearly completed geometry. This is unfortunate, since it is too late to help the team compare or evaluate strategies that rely on geometry, such as natural ventilation, orientation, passive solar, and others.

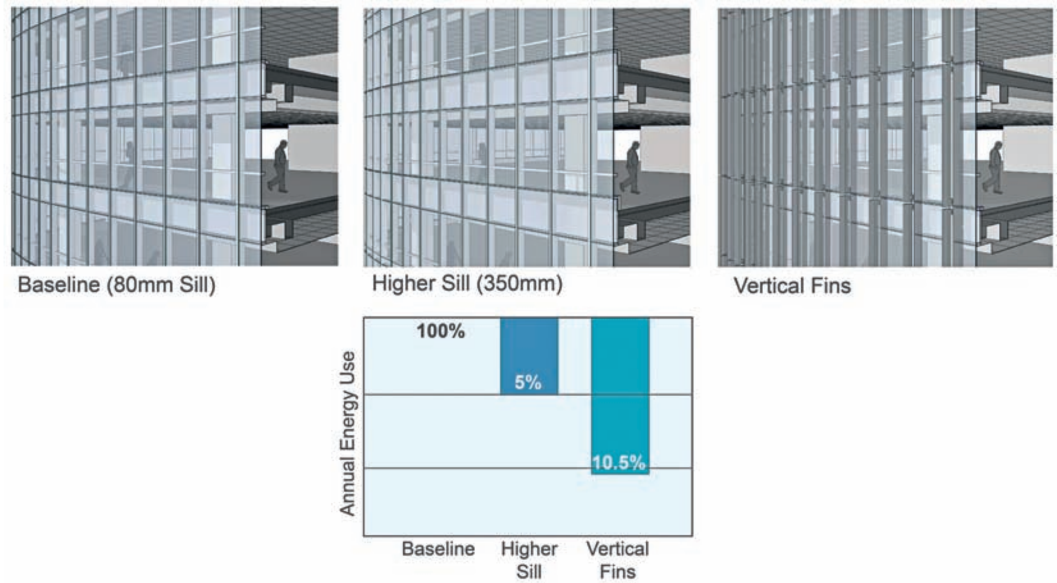
Some simulations are best done within the design team in an architecture firm, some are best done by professional energy analysts who can be housed in architecture firms, mechanical design firms, or energy analysis firms, others are best done within a mechanical design firm.

Architects generally lead the design efforts that affect shading, daylighting, geometry, and orientation, so they need immediate access to modeling of those systems to make the right decisions. An in-house program that covers these topics can be useful for quick studies in early design.

Specialist energy analysts within architecture firms are generally not mechanical designers. They are good at setting up and running an energy simulation, producing compliance documents for energy codes or LEED submittals, validating as-built with predicted performance, and checking a model done by an outside engineer. However, they need to spend time researching a mechanical system they are not familiar with in order to accurately model it.

Professional energy analysts, wherever they are housed, run most energy and airflow models. They can provide parameters to guide architects' design simulations, such as: target peak loads, specific solar irradiation targets, target lighting use factors, insulation or UA targets, and other parameters. This allows the technical knowledge of the engineer to guide the intuitive problem-solving skills of the architect.

The mechanical design firm creates other types of models to size and compare mechanical systems. Mechanical firms with specialists can produce the right energy models for detailed analyses that are necessary later in design—some are also very good at modeling early in design.



10.20

Study of energy use reductions comparing a baseline option against an option with a higher sill and another with vertical shading. This study used Autodesks's Green Building Studio.

Source: Courtesy of Callison.

WORKING WITH ENERGY ANALYSTS

The profession of energy modeling is a practice. Like medicine, methods are continuously being evaluated, improved incrementally by testing, and sometimes methods are abandoned. No two energy analysts will abstract a problem in exactly the same way, meaning that very rarely will two energy analysts get the exact same results for complicated projects. In addition, most sophisticated whole building energy simulation (WBES) analysts and firms have created custom scripts to automate common processes or coax more realistic outputs from the engine.

Technical project delivery issues aside, the reputation of an architect rides on aesthetics and function of a space, while an engineer's reputation rides on producing comfort. For this reason, engineers are rewarded for being conservative in their designs. Designing a system too specifically to a set of assumptions, especially occupant behaviors, can cause problems. For example, users may be expected to deploy blinds during the hottest days of the year; if this doesn't happen, a minimally-sized cooling system will be unable to cope with the loads, creating discomfort and the perception of design failure.

Mechanical design and energy analysis are separate skills, often done by different individuals. While they overlap, energy modeling must consider electrical, lighting, and envelope systems that are not necessarily part of a mechanical engineer's scope or expertise, while mechanical designers stay current with systems, performance, and optimum layouts. Mechanical designers and energy analysts are often housed within the same firm, though this is not necessary.

Some engineers are very good at running early design studies; however, most instinctively want to dive deeper immediately, which cannot be done within concept design budgets and timeframes. You may recall from Chapter 1 that many architectural firms with in-house engineers also have a team of simulation specialists for early design, since many engineers are overwhelmed by the number of unknowns and variables in early design.

There are many types of models that engineers can create. Some of these are listed in the introduction to this chapter. Each study requires time, a fee and interaction between architect and analyst. When requesting an energy study, the architect should clearly communicate their intent regarding the use of the study, and the analyst should choose the best modeling types to test the options. Compliance models for LEED, for example, are different from models used to size systems, which are different from models to compare detailed options, which are unique from quick models set up in early design. One model cannot necessarily be used for another purpose.

2009 Seattle Energy Code Building	Annual Energy Cost		See Note #	Annual Electricity Usage (kWh)	Annual Base EUI kBtu per sf	Annual CO_2 Emissions lbs.
	$42,878	-	-	659,654	64.3	963,095

Basis of Design	Annual Energy Cost (see note)	Percent Savings	See Note #	Annual Electricity Usage (kWh)	Annual Base EUI kBtu per sf	Annual CO_2 Emissions lbs.
	$40,275	-	-	619,617	60.4	904,641

LEED-NC EAc1 Point Thresholds[3]

12% - 1	30% - 10
14% - 2	32% - 11
16% - 3	34% - 12
18% - 4	36% - 13
20% - 5	38% - 14
22% - 6	40% - 15
24% - 7	42% - 16
26% - 8	44% - 17
28% - 9	48% - 19

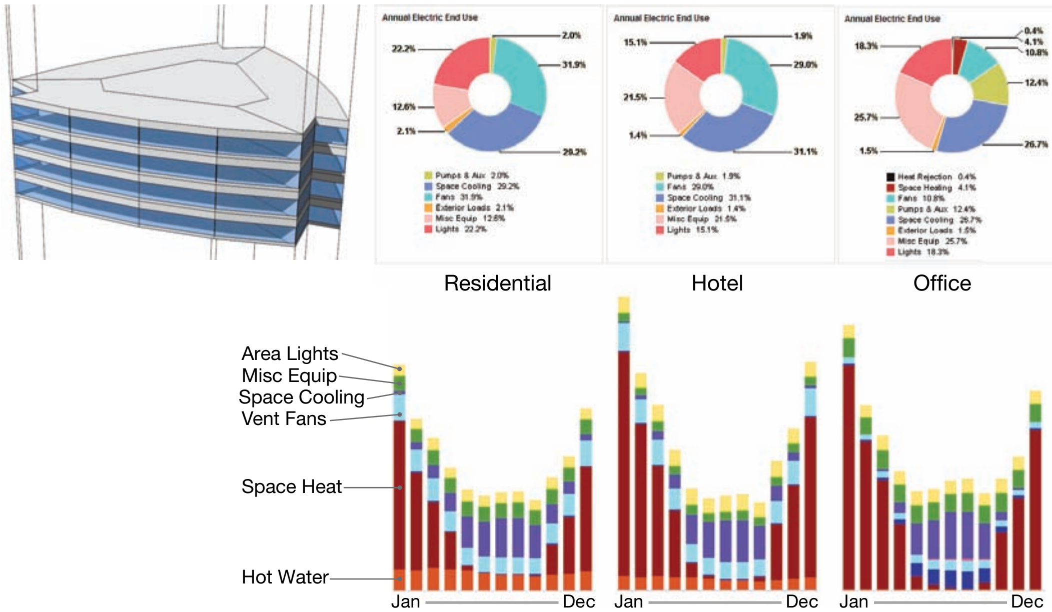
Utility Details			
Electricity Rate ($/kWh)	Gas Rate ($/therm)	Electricity CO_2 (lbs./kWh)	Gas CO_2 (lbs./therm)
$0.065	N/A	1.46	11.6

ECM #	Individual Energy Efficiency Measure	Location	See Note #	Additional Electricity Savings (kWh/yr)	Additional Energy Cost Savings	Additional Energy Cost Percent Savings	Total Cost	Incremental First Cost	Incentives	Simple Payback (yrs)	Site EUI kBtu/sf-yr	Site EUI % Reduction vs BOD	Additional Annual CO_2 Reduction lbs.	Additional Annual CO_2 Reduction Additional %
Preliminary Energy Conservation Measures for Consideration														
1	Tuned/high performance glazing to maximize daylight harvesting & comfort. Assembly U-Value 0.32 SHGC 0.25 (West), SHGC 0.35 (All Others)	Envelope	1	9,370	$609	1.5%	$503,842	$83,950	$3,092	27.1	59.5	1.5%	13,680	1.5%
2	High performance wall assembly U-Value 0.05 (SEC U-Value 0.055 for steel framed walls)	Envelope	2	2,867	$186	0.5%	TBD	TBD	$946	N/A	60.2	0.4%	4,186	0.5%
4	Mixed mode ventilation, email notification tied to acceptable outside air temperature	HVAC/ Envelope	4	7,352	$478	1.2%	$30,050	$6,500	$1,691	3.8	59.7	1.1%	10,734	1.2%
5b	VRF for decentralized and central unit w/Demand Control Ventilation for offics spaces	HVAC	5b	112,088	$7,286	18.1%	$1,052,529	$453,358	$25,780	17.6	49.5	18.0%	163,648	18.1%
6	Workshop exhaust heat recovery for make up air	HVAC	6	36,206	$2,353	5.8%	$17,537	$17,537	$8,327	2.1	56.9	5.8%	52,861	5.8%
7a	Use Basement Film/Video Media room HVAC unit condenser heat to preheat make up air for workshop areas	HVAC	7a	4,672	$304	0.8%	$5,000	$5,000	$1,075	4.7	60.0	0.7%	6,821	0.8%
9	Exterior lighting 50% better then SEC	Ext Lighting	9	4,964	$323	0.8%	$35,204	$12,180	$1,142	10.7	59.9	0.7%	7,247	0.8%
10	Install skylights over 4th floor open office space and implement daylight harvesting throughout	Int Lighting	10	6,242	$406	1.0%	$36,874	$29,500	$1,436	20.5	59.8	1.0%	9,113	1.0%
11	Reduce lighting power density in office spaces to 0.7 W/sf (SEC 0.9W/sf allowance). Reduce lighting by 20% better then SEC for other space types	Int Lighting	11	19,516	$1,269	3.1%	$443,551	$121,478	$4,489	27.1	58.5	3.1%	28,493	3.1%
12	Discretional control of lighting fixtures by occupants through the use of addressable ballasts	Int Lighting/ Behavioral	12	$0	NA	NA	$0	$51,126	$2,607	19.6	60.4	NA	N/A	N/A
13	Tenant Intuitive M&V/usage awareness to encourage occupants to work in a sustainable manor. (ThinkEco/Enmetric possibly paired with PeoplePower interface)	Social/ Behavioral	13	$0	NA	NA	N/A	N/A	N/A	N/A	60.4	NA	N/A	N/A
~~14b~~	~~Utilize cloud computing services for 50% of digital media and reduce onsite server requirements~~	~~Process Loads~~	~~14~~	~~59,943~~	~~$3,896~~	~~9.7%~~	~~N/A~~	~~N/A~~	~~N/A~~	N/A	~~54.6~~	~~9.6%~~	~~87,517~~	~~9.7%~~
15	Plug load management system to shut off non-critical devices during unoccupied and/or times when not in use	Process Loads	15	$0	NA	NA	N/A	N/A	$680	N/A	60.4	NA	N/A	N/A
16	Energy Star appliances	Process Loads	16	Negligible	NA	NA	N/A	N/A	N/A	N/A	60.4	NA	N/A	N/A
17	9.5kW Photovoltaic Array	Onsite Generation	17	9,431	$613	1.5%	$0	$31,204	$2,169	14.4	59.5	1.5%	13,769	1.5%
20	Regenerative Elevators	Process Loads	20	5,304	$345	0.9%	$130,000	$15,000	$1,220	12.3	59.9	0.8%	7,744	0.9%
	Totals								$54,653					
Interactive combinations in the design														
A	1, 2, 4, 5b, 6, 7a, 9, 11, 17, 20	NA	NA	191,234	$12,430	30.9%					41.8	30.8%	279,202	30.9%

10.21

Energy efficiency measures are often used to compare costs and energy savings of proposed building strategies based on whole building energy simulations. Each of the options has been run through the ASHRAE 90.1 energy model to determine projected energy savings and energy cost savings.

Source: Courtesy of Glumac Engineers.



10.22

A concept-level floor plate with 60% glazing was uploaded to Autodesk's Green Building Studio for an automated energy analysis. The vertical, mixed use project includes hotel, residential, and office. Annual electricity use pie charts for each typology show that lighting is a bigger concern for residential and office than for hotel, equipment is a large energy user for hotel and office, and fan power is a much larger energy use for residential and hotel than for office. Heating is assumed to come from gas and is not shown on the pie charts. Below, bar charts show monthly overall energy use includes gas and electricity, outlining a profile that can be used to begin sorting through early design strategies.

Source: Courtesy of Callison.

WHOLE-BUILDING ENERGY SIMULATIONS (WBES)

Whole-building energy simulations (WBES) are a complex and time-consuming endeavor, trading flexibility for higher accuracy. It can take from a week to a month to input, calibrate, and complete a whole building energy simulation for a medium to large project. The result is a very detailed look at a very specific building design. An engineer can interpret the results, but most architects' eyes glaze over when shown pages of resulting numbers.

Once a WBES has been set up, testing the energy impact of changed parameters such as wall U-values, glazing properties, and other material assignments seems simple—a 20% better U-value for an opaque wall can be changed within the model easily, and the model may report that it reduces energy use by 4%. However, changing the U-value of the opaque wall decreases the peak loads and could, therefore, decrease the mechanical system, airflow, and ductwork size.

The actual energy savings from increasing the insulation value of the wall may be 8% or higher, but this result is not reported without a redesign of the mechanical system. Since engineers get the fee and the time to fully design and model a limited number of systems, accurately assessing each change is beyond their normal scope, and so any additional savings are guessed at or not included in a typical analysis.

Most WBES cannot easily test geometric change, either. An increase in floor plate or a small geometric change can be estimated by simply multiplying the WBES output by a reasonable factor, but actually re-designing all of the systems to best incorporate this within the energy model is often beyond the fee and time allowed.

Since geometrical comparison is critically important to early design stages of low-energy projects, a quick workflow from architectural model to energy model is ideal. Building information modeling (BIM) promises this translation but has yet to deliver. Few projects have usefully traded geometry between architect and energy analyst without requiring significant redrawing effort. As an exception, LMN Architects have developed a method of exchanging 3D models of glazing locations with engineers, that automatically update the energy models and result in quick assessments of energy use. Quicker, but less accurate, shoebox models are often created to specifically answer a question, and then calibrated by an architect or engineer in a matter of hours.

CONCLUSION

Architects need to engage in the energy performance of their buildings so they can make the right early design moves. While it is no substitute for professional guidance, architect-usable software is becoming more automated and advanced. Architects can learn to run early energy use studies on typical buildings, helping them make better geometric decisions. Quick shoebox models can help a team understand the most important aspects of a building design to improve performance.

Architects, energy modeling analysts, and engineering firms can each run different types of models that are integral to the design process and provide the best balance of speed, design flexibility, and rigor.

ADDITIONAL RESOURCES

Advanced Energy Design Guides for various building types are designed to help project teams reduce energy use by 50%, see ASHRAE 90.1–2004, available at: https://www.ashrae.org/standards-research–technology/advanced-energy-design-guides.

ASHRAE Handbook of Fundamentals. Numerous papers published by the International Building Performance Simulation Association, including "The Architect as Performer of Energy Simulation in the Early Design Stage" (2009).

Project type:
Demonstration Center

Location:
Rancho Cucamonga, California

Design/modeling firm:
HMC Architects

10.1 TRADE-OFF ANALYSIS

Energy studies require the integration of all components, including glazing and opaque wall selection, shading, daylight, airflow, and other aspects.

Overview

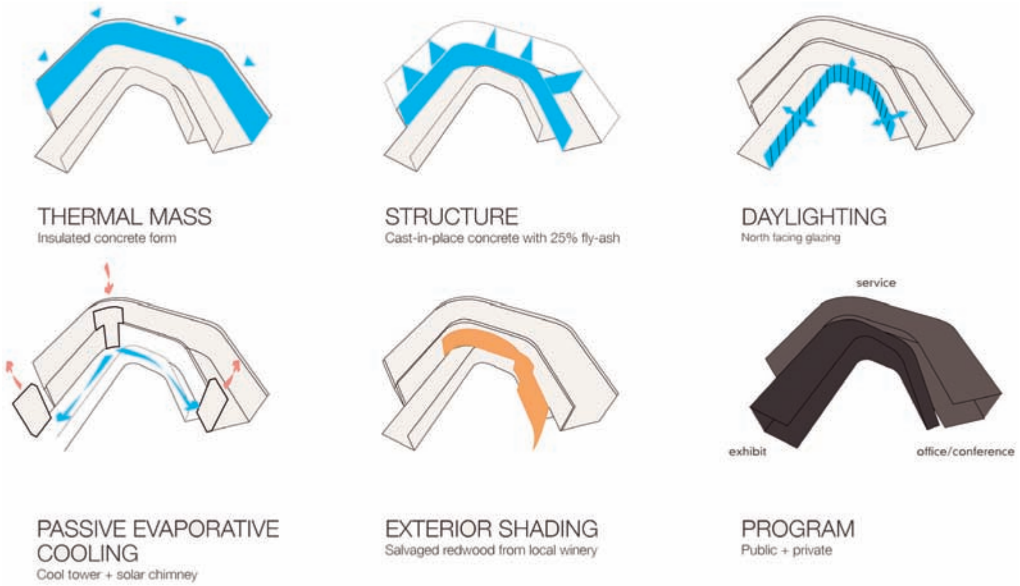
The Frontier Project's sustainability goals were driven by the client, the Cucamonga Valley Water District, to include significant energy and water reductions compared to California's already stringent Title 24 requirements. The project was certified LEED Platinum, and achieved a total of 45% energy reduction below Title 24 and 55% water reduction, with an energy return on investment for green systems of around 6.8%. In addition, the actual energy performance closely tracks the modeled performance.

Though HMC is an architecture firm, they employ several design simulation specialists in a group they call ArchLab. All of the energy and daylighting analyses, as well as the post-occupancy evaluation, were done in-house by ArchLab in close collaboration with the design team, to ensure they had immediate access to modeling without the layers of communication and contract issues that are part of many energy modeling efforts. Due to this close collaboration, many of the energy simulation outputs were not documented formally since the results were immediately discussed with the team to inform their decision-making. A small sample of the simulation performed is shown in this case study.

10.23

Photo looking south.

Source: © *Ryan Beck.*



10.24

ArchLab's diagrams.

Source: Courtesy of HMC ArchLab.

Simulation tools were used for a variety of purposes, from choosing the materials based on embodied energy and life cycle analysis, to shaping the building's daylighting, airflow, and energy use.

Doing the simulations in-house also allowed the team to more easily conduct a post-occupancy evaluation of thermal comfort, energy, and daylight, and then interpret the data.

Simulation

From the earliest phases, the design was modeled against a Title 24 baseline building using EnergyPro. This allowed a progression from early designs that were 5% better than Title 24, to the final design which was 36% better, and 45% better with photovoltaics included.

Based on climate analysis, initial massing studies located the mostly opaque walls to the south and west to avoid over-heating from direct solar irradiation. A glassy façade was located facing north to visually connect with the landscape. Another glassy façade faced east, though this façade was shaded by a curvilinear stair that was designed specifically to reduce solar loads, and also by the airflow stack which took on a mass expression.

Envelope and Daylighting

Once the building massing was beginning to be set, envelope options were tested, since the framing of the building would determine some of the resulting aesthetic expression. Framing materials were considered for energy performance, cost, speed of construction, and structural integrity. Five framing types were tested during design, shown in Figure 10.27. The thermal lag and lack of thermal bridging within the ICF construction were found to reduce conduction-based peak and annual loads and were ultimately proven to be the best performer of the framing types considered.

Several glazing types were then tested for energy and daylighting performance, including a variety of Tvis, SHGC, and U-value characteristics. One of the modest-priced glazing types seemed to achieve the best balance between energy performance and life cycle cost. When the glass was considered with the necessary fire rating, however, the fire-rated color of the glass did not meet the design team's goals. For this reason, the glass specification was switched to the second choice in terms of performance, although it had best life cycle cost. With further analysis, this second glazing choice was proven to be able to deliver the targeted performance levels.

Roof assemblies, including intensive and extensive green roofs, were compared for life cycle savings as well. Groups of envelope strategies were then bundled to determine the optimum envelope package, compared in Figure 10.27.

HMC

Building Envelope Life Cycle Cost Analysis Summary
3/12/2007

Frontier Project
HMC Project Number 2286002

Total Envelope Analysis

	Building Envelope Alternative	Roof	Exterior Walls	Glazing	Title 24 Compliance Margin*	Life Cycle Savings**	Total Building First Cost***
Base	Typical Market Practice	Rigid insulation (R-28), modified bitumen roof, white elastomeric coating	6" metal studs, batt insulation (R-19), exterior stucco	1/4" monolithic PPG Optigray tint	-9.4%	n/a - Base Case	$10,167,314
Alt 1	Title 24 Default Assemblies	Rigid insulation (R-19), modified bitumen roof, white elastomeric coating	6" metal studs, batt insulation (R-13), exterior stucco	1" IG PPG SolarbanXL	-4.0%	($4,186)	$10,237,743
Alt 2	LCC Optimized	Rigid insulation (R-28), white TPO membrane	Insulating Concrete Forms (8" cavity), cementitious stucco topcoat, silicate paint	1" IG PPG Solarban 60 clear	18.5%	$18,964	$10,224,984
Alt 3	Cutting-Edge Technologies	Intensive green roof on concrete deck	Autoclaved aerated concrete block (10" wythe), cementitious stucco topcoat	1" IG PPG SolarbanXL Starphire	16.4%	($329,909)	$10,258,157
Alt 4	Strawbale	Rigid insulation (R-28), white TPO membrane	30" strawbale, cementitious stucco topcoat	1" IG PPG Solarban 60 clear	3.0%	($12,754)	$10,281,122

* Assumes Title-24 default mechanical and lighting systems.
** Negative numbers (in parentheses) indicate life cycle cost as opposed to savings.
*** Assumes default non-envelope costs.

Exterior Wall Analysis

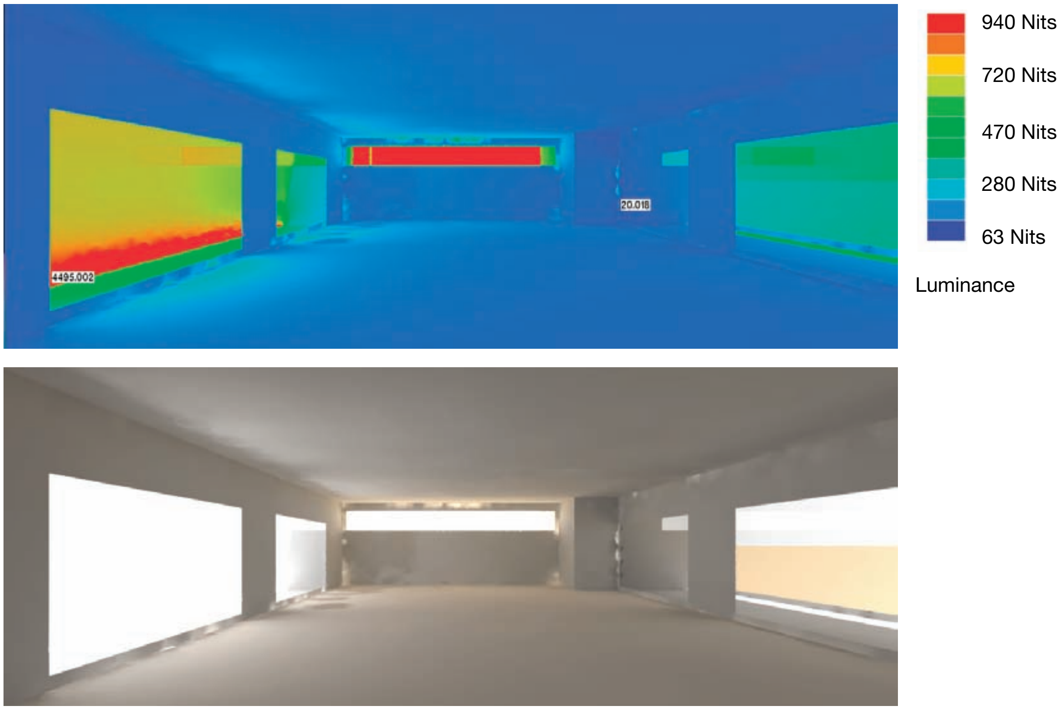
	Building Envelope Alternative	Roof	Exterior Walls	Glazing	Title 24 Compliance Margin*	Life Cycle Cost Savings**	Unit First Cost (sf)
W0	Typical Market Practice	Rigid insulation (R-28), modified bitumen roof, white elastomeric coating	6" metal studs, batt insulation (R-13), exterior stucco	1/4" monolithic PPG Optigray tint	9.0%	n/a - Base Case	$27.60
W1	Block Wall	Rigid insulation (R-28), modified bitumen roof, white elastomeric coating	8" fully grouted concrete block, 4" metal furring, R-13 batt insulation	1/4" monolithic PPG Optigray tint	5.8%	($65,938)	$34.50
W2	ICF	Rigid insulation (R-28), modified bitumen roof, white elastomeric coating	Insulating Concrete Forms (8" cavity), cementitious stucco topcoat, silicate paint	1/4" monolithic PPG Optigray tint	9.6%	($8,213)	$33.25
W3	AAC	Rigid insulation (R-28), modified bitumen roof, white elastomeric coating	Autoclaved aerated concrete block (10" wythe), cementitious stucco topcoat	1/4" monolithic PPG Optigray tint	3.9%	($27,288)	$36.50
W4	Strawbale	Rigid insulation (R-28), modified bitumen roof, white elastomeric coating		1/4" monolithic PPG Optigray tint	7.7%	($48,330)	$38.75

* Assumes Title-24 default mechanical and lighting systems.
** Negative numbers (in parentheses) indicate life cycle cost as opposed to savings.

10.25 and 10.26

Envelope LCC summary.

Source: Courtesy of HMC ArchLab.



10.27

Luminance analysis of the conference space looking north to dertermined light quality and the ability to incorporate a video screen without closing the shades, June 21 noon.

Source: Courtesy of HMC ArchLab.

For visual performance, daylight simulations were conducted in critical rooms such as the exhibition area and the first floor conference room. Both illuminance and luminance were studied, with the design eventually meeting LEED criteria (see Figure 10.28).

An LCD screen for presentations was one of the desired features within the conference space, so daylight levels were tested to ensure that walls were not above 450 candelas/m^2, which would compete with the screen.

Natural Ventilation, HVAC, and Comfort

Airflow through the building was designed to use natural buoyancy and direct evaporative cooling. The stack-driven exhaust (1) in each wing was expressed, as well as the central air intake (2) that housed the direct evaporative cooling equipment (inside 2). Early studies using FloVent software considered several scenarios to size the airflow intake (3) and exhaust (4), ensuring that cool air entering would reach the floor level and buoyancy would be great enough to remove warm air under various external and internal conditions. Each option was tested against resulting indoor comfort levels. The solar chimneys were sized at a 1:5 proportion, with the interior painted a dark color to absorb solar energy near the top of each stack to help drive the stack effect. A grille over the top prevents rain from entering the stack. The final design included a fan to assist with air intake.

In addition to natural ventilation, underfloor displacement ventilation is used, along with evaporative cooling and an energy recovery ventilator with 100% outside air, while the second floor uses a VRF/VRV system designed by the mechanical engineer. Visitors to the building can peek at the main components of the HVAC system, located behind a glass wall on the first floor.

After construction, the team assessed their performance by conducting post-occupancy surveys of thermal and visual comfort levels while simultaneously measuring interior temperature and humidity levels. These studies are to ensure that designs achieve the high goals set for each project, and are also used by HMC to validate and calibrate their simulation results.

The temperature profiles show that the spaces did stay within the comfort range for the days studied. The most extreme conditions were at the first floor reception, with temperatures up to 85°F with 25%

10.28

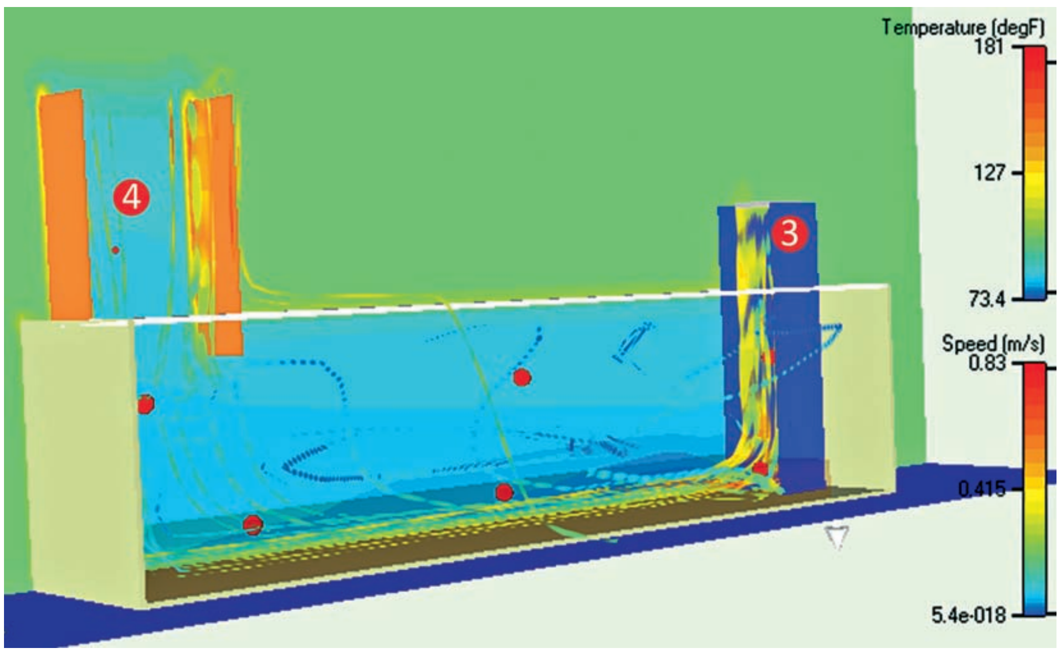
Photo looking southwest.

Source: © *Ryan Beck.*

10.29

CFD study of intake and solar chimney.

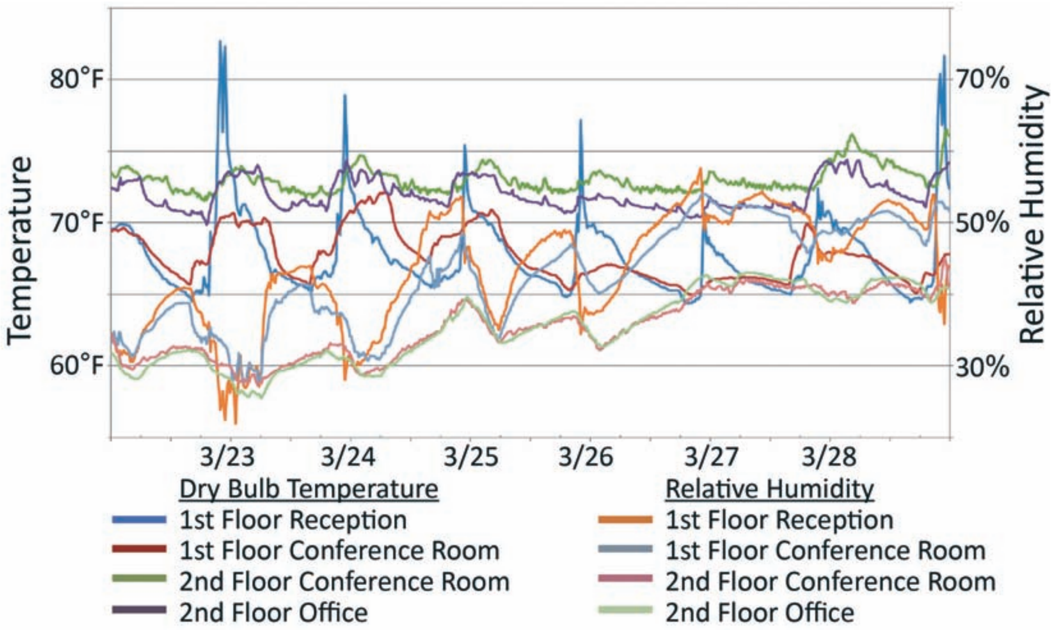
Source: Courtesy of HMC ArchLab.



RH during part of one day. It meets the Adaptive comfort zone standard due to the prevailing outdoor temperature.

All of the full-time occupants of the building, who work primarily on the second floor, participated in the survey. The survey shows that they were satisfied with the thermal conditions, with less than 17% slightly dissatisfied. None reported that they were hot or very hot during the summer or that they were cool or very cool in the winter, illustrating that the building systems are adequately designed to meet peak loads.

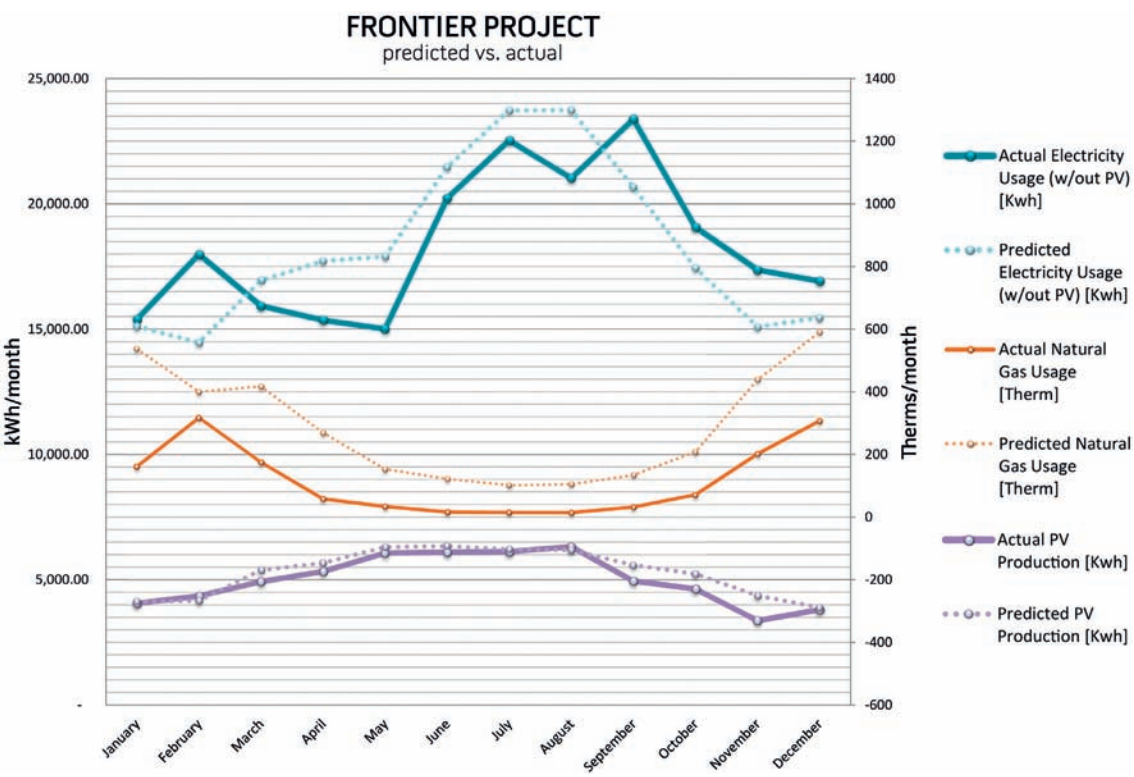
HMC ArchLab also collected the energy use data and compared it to the LEED energy model submittal. Due to the close interaction of the design team with the energy modeling team, the modeled result and the real energy consumption are very similar, with discrepancies likely due to normal weather variations.



10.30

Temperature and relative humidity in various spaces from a post-occupancy evaluation over several days.

Source: Courtesy of HMC ArchLab.



10.31

Actual energy use compared to predicted energy use over first year.

Source: Courtesy of HMC ArchLab.

10.2 EARLY CONCEPT TRADE-OFF ANALYSIS

Project type:
Visitor center

Location:
St. Augustine, Florida

Design/modeling firm:
Lord, Aeck, & Sargent

Determining a combination of strategies to achieve energy goals at design kick-off provides reasonable targets for glazing percentage, overall insulation value, shading depth, lighting energy, and other strategies.

Overview

For a new 17,000 ft^2 visitor center for the historic Castillo de San Marcos National Monument in St. Augustine, federal regulations required the building to achieve energy performance 30% better than an ASHRAE 90.1–2004 baseline, or approximately 29.4 kBtu/ft^2/year.

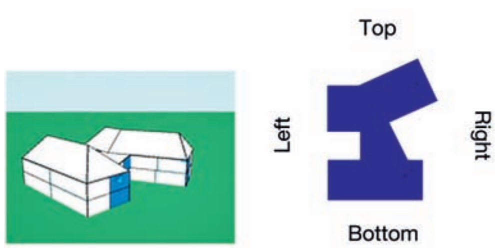
While architecture firm Lord, Aeck, & Sargent (LAS) does not have an in-house mechanical design team, it does have in-house energy modeling professionals to ensure that project teams have access to meaningful feedback in early design. The energy modeling team used the relatively new Sefaira Concept software for this study.

Simulation

The team wanted to understand the relative effectiveness of additional insulation, the window-to-wall ratio, SHGC, horizontal shading, and other sustainable strategies before massing options were selected. These efficiency measures (EEMs) were then tested to see which combination would collectively reach the EUI goal.

A 3D massing model of one design option was built in SketchUp and imported into Sefaira Concept for analysis. Simple controls within the software were be used to adjust glazing percentages for each façade, allowing parametric tests to determine the relative energy performance of various glazing percentages. Window-to-wall ratios from 25% through 40% were tested, with 30% being selected as a reasonable target to improve energy performance by around 5% over the baseline scheme with 50% glazing.

Each EEM was tested to determine its individual contribution to energy performance. Shading, for example, was tested at 1′, 2′, 3′, and 4′ depths. The project team used the 2′ depth as it provided reasonable cooling energy savings. As the design progressed, the team refined this dimension for each façade. Knowing that this depth of shading had around a 2% effect on energy use was helpful in determining the relative importance of shading.



Floor	Envelope Area to Volume Ratio (ft^2/ft^3)	Floor Area
1	0.069 ft^2/ft^3	8,409 ft^2
2	0.058 ft^2/ft^3	9,438 ft^2
2	0.061 ft^2/ft^3	17,846 ft^2

10.32

A simple 3D model was drawn in early design, with general statistics calculated to the right so the user can confirm taht the software interpreted the 3D model correctly.

Building on site NPS CASA

Run Analysis | New Strategy | Export | Add Result

	Annual Energy Consumption kBTU	Annual Energy Use per Gross Internal Area kBTU/ft2	Annual Utility Cost $	Annual Space Cooling kBTU
Baseline + Measures	749,515	42	52,651	308,208
▽ shading_4'	730,245 ↓3%	41 ↓2%	51,295 ↓3%	285,744 ↓7%
[All] Depth (4.0 ft)				
▽ shading_3'	733,218 ↓2%	41 ↓2%	51,505 ↓2%	289,501 ↓6%
[All] Depth (3.0 ft)				
▽ shading_2'	737,214 ↓2%	41 ↓2%	51,786 ↓2%	294,301 ↓5%
[All] Depth (2.0 ft)				
▽ shading_1'	742,449 ↓<1%	42 0%	52,154 ↓<1%	300,344 ↓3%
[All] Depth (1.0 ft)				
▽ Wall_Rvalue20	744,086 ↓<1%	42 0%	52,273 ↓<1%	306,485 ↓<1%
[All] Wall Type (Stud)				
[All] Wall Thermal Resistance (20.00 ft²·h·°F/BTU)				
▽ Wall_Rvalue15	746,351 ↓<1%	42 0%	52,432 ↓<1%	307,909 ↓<1%
[All] Wall Type (Stud)				
[All] Wall Thermal Resistance (15.00 ft²·h·°F/BTU)				
▽ Wall_Rvalue10	745,481 ↓<1%	42 0%	52,369 ↓<1%	306,214 ↓<1%
[All] Wall Type (Concrete Block)				
[All] Wall Thermal Resistance (10.00 ft²·h·°F/BTU)				
▽ Glazing_SeriousSG5	734,722 ↓2%	41 ↓2%	51,616 ↓2%	299,503 ↓3%
[All] Facade Glazing U-Factor (0.30 BTU/h·ft²·°F)				
[All] Facade Glazing SHGC (0.23)				
▽ Glazing_ViraconVUE1-40	731,223 ↓2%	41 ↓2%	51,368 ↓2%	293,234 ↓5%
[All] Facade Glazing U-Factor (0.40 BTU/h·ft²·°F)				
[All] Facade Glazing SHGC (0.2)				
▽ Glazing_Solarban70XL	741,817 ↓1%	42 0%	52,114 ↓1%	305,410 ↓<1%
[All] Facade Glazing U-Factor (0.40 BTU/h·ft²·°F)				
[All] Facade Glazing SHGC (0.25)				
▷ WWR25	715,793 ↓4%	40 ↓5%	50,283 ↓4%	275,719 ↓11%
▷ WWR30	722,465 ↓4%	40 ↓5%	50,752 ↓4%	282,187 ↓8%
▷ WWR35	729,183 ↓3%	41 ↓2%	51,224 ↓3%	288,675 ↓6%
▷ WWR40	735,928 ↓2%	41 ↓2%	51,697 ↓2%	295,173 ↓4%

10.33

Screenshot showing several Energy Efficiency Measures that were tested.

Source: Courtesy of Lord, Aeck & Sargent.

10.34

Final bundle of EEMS that reach the target EUI, including a 20% lighting reduction that was input manually.

Source: Courtesy of Lord, Aeck & Sargent.

Run Analysis / New Strategy	Annual Energy Consumption kBTU	Annual Energy Use per Gross Internal Area kBTU/ft2	Annual Utility Cost $	Annual Space Cooling kBTU	Annual Space Heating kBTU
Baseline + Measures	**749,515**	**42**	**52,651**	**308,208**	**36,713**
▸ Bundle2: Envelope + HighEffRoof	712,633 ↓5%	40 ↓5%	49,385 ↓6%	242,790 ↓21%	140,411 ↑282%
▾ Bundle1: Envelope + GSHP_VRF	561,917 ↓25%	31 ↓26%	39,504 ↓25%	182,336 ↓41%	28,870 ↓21%
▷ WWR30	722,465 ↓4%	40 ↓5%	50,752 ↓4%	282,187 ↓8%	35,684 ↓3%
▷ Glazing_ViraconVUE1-40	731,223 ↓2%	41 ↓2%	51,368 ↓2%	293,234 ↓5%	33,394 ↓9%
▷ Wall_Rvalue10	745,481 ↓<1%	42 0%	52,369 ↓<1%	306,214 ↓<1%	34,673 ↓6%
▷ shading_2'	737,214 ↓2%	41 ↓2%	51,786 ↓2%	294,301 ↓5%	38,318 ↑4%
▷ HVAC_GSHP_VRF	596,680 ↓20%	33 ↓21%	41,942 ↓20%	212,826 ↓31%	33,144 ↓10%
-20% Lighting Energy Reduction		29 = EUI			

The strategies were then bundled to determine the preferred group of strategies to achieve the target EUI at a conceptual level. As they were refined through the design process, the design was periodically re-tested to ensure that the team was on track.

Sefaira was in beta testing during the early phases of this project, so the energy analysts at LAS used work-arounds to estimate additional performance measures due to a ground source heat pump and improved lighting efficiency. Improved lighting efficiency was conservatively used to only reduce electric lighting loads, so the cooling savings associated with lighting energy reductions were not taken into account.

10.3 OPTIMIZATION ANALYSIS

While many energy simulations focus on trade-offs considered one at a time, an optimization analysis uses parametric inputs to automate hundreds or thousands of energy model runs. The results can be graphed to illustrate areas that are the most critical for the designer to focus on.

Project type:
Existing building converted to office

Location:
Bremerton, Washington

Design/modeling firm:
Rice Fergus Miller/Ecotope Engineers

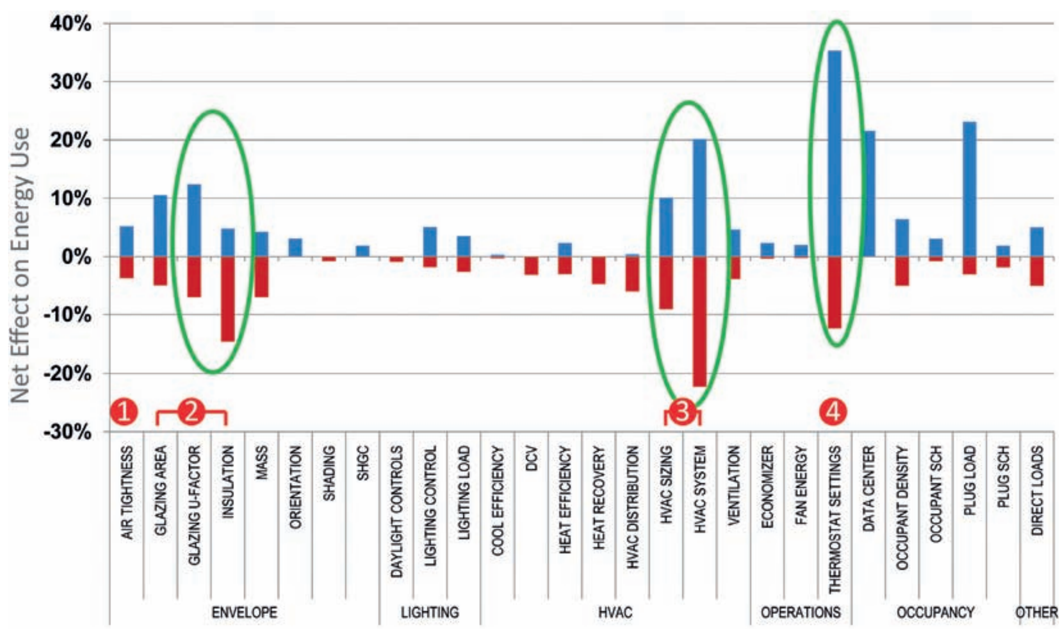
Overview

At the kick-off eco-charette for the Rice Fergus Miller office project, the goal of creating a Net Zero Energy ready building was agreed on by the project team. In addition, the project had to cost less than typical new construction.

Ecotope used methods from a paper they had collaborated on (NBI, "Sensitivity Analysis") as a starting point for this analysis to inform the design of the Rice Fergus Miller offices in Bremerton, Washington. This type of analysis allowed a starting point for the team to ensure that the most effective strategies were pursued. The strategies eventually used on the project reflected the most cost- and energy-effective design. Since the project entailed refurbishing an abandoned building, unique conditions associated with the existing building made certain energy efficiency measures easier and others more difficult.

Simulation

The simulations used the existing building being renovated for the geometry, with the other inputs from the Commercial Reference Building Models prototype to set up a typical office building using eQuest



10.35

Optimization analysis results, showing potential energy significance of tested options.

software. Excel was used to develop a database of multiple parameters for each of the eQuest defaults, and then the eQuest batch processing utility was used to run hundreds of simulations to test combinations of the variables considered in this study. Some parameters, including those relating to HVAC systems, were fairly complex and required work-arounds for less prevalent systems.

Each variable tested was given a low, medium, and high value based on existing conditions, code-compliant inputs, and high-efficiency alternatives, respectively. Then each possible combination of alternatives was run as an annual energy model to determine the relative effects of the low, medium, or high choice on overall energy use. Those aspects with high effects on energy use, such as glazing and insulation (1), HVAC system (2), and thermostat settings (3) became the focus of energy-efficiency efforts. Aspects that were shown to be less able to affect overall energy use, such as shading and heating efficiency, were addressed later (4).

For example, high insulation levels were shown to decrease energy use by 15% with the best option considered, while potentially could increase energy use by around 5% if done poorly.

The low, medium and high glazing properties were those currently in the existing building, ASHRAE 90.1 minimums, and high performance triple glazing, respectively. For HVAC options they included variable air volume, single zone PRTU, and VRF heat pump. Thermostat settings included 74° Cool /72° Heat, 76°F Cool /70°F Heat with night setback, and 80°F Cool /68°F Heat with night setback. Geometric and HVAC options were more difficult to test using an optimization analysis, since each one requires a thoughtful design.

Interpretation

The results of each of the many simulations were compiled and graphed to determine each parameter's contribution to energy use in the best and worst cases. These were used to efficiently guide the project team to study the most effective energy reduction strategies.

10.4 PASSIVHAUS PHPP

Project type:
Single-family residential

Location:
Knox, Maine

Design/modeling firm:
EcoCor Design/Build, LLC

The Passivhaus system uses a spreadsheet-based software to simulate energy use using very detailed calculations. Thousands of Passivhaus houses built in Europe have verified the accuracy of the underlying algorithms. Passivhaus projects are required to meet energy use intensity thresholds for heating and overall energy use.

Overview

The Passivhaus standard was created in Germany, and is widely popular in the cooler climates of Europe. It is also being adopted by many of the leading practitioners in the US that work on smaller projects. The Passivhaus (PH) standard uses the energy modeling tool, called Passivhaus Planning Package (PHPP), which is a comprehensive spreadsheet-based heat balance software. For projects that follow Passivhaus standards, it predicts energy use far more accurately than most other software, and includes many inputs that are ignored by other energy modeling programs, especially thermal bridging.

Passivhaus houses are designed with minimal heating requirements, less than 4.75 kBtu/ft^2 of "treated" floor area/year or peak heating below 3.17 Btu/ft^2/hr, in even extremely cold climates. The standard is not prescriptive, but is often achieved using the most cost-effective combination of high insulation values (such as R-50 walls), a tight envelope (verified with required pressurization testing), reduction of thermal bridging (using THERM software calculations to evaluate details at façade intersections), the use of heat recovery for fresh air supply, and the use of triple-glazed windows with

10.36

Photograph from southeast.

Source: Courtesy of Chris Corson.

		Annual Heat Demand:		3.11	kBTU/(ft²yr)								
Window Area Orientation	Global Radiation (Cardinal Points)	Shading	Dirt	Non-Perpendicular Incident Radiation	Glazing Fraction	SHGC	Reduction Factor for Solar Radiation	Window Area	Glazing Area	Glazing Area as % of Gross Floor Area	Average Global Radiation	Transmission Losses	Heat Gains Solar Radiation
	kBTU/ft²yr	0.75	0.95	0.85				ft²	ft²		kBTU/ft²yr	kBTU/yr	kBTU/yr
North	36	0.75	0.95	0.85	0.599	0.49	0.36	14.3	8.6	1.2%	36	368	92
East	95	0.73	0.95	0.85	0.692	0.49	0.41	86.6	59.9	8.1%	95	1986	1658
South	194	0.78	0.95	0.85	0.751	0.49	0.47	220.7	165.7	22.5%	194	4904	9968
West	102	0.80	0.95	0.85	0.718	0.49	0.46	96.7	69.4	9.4%	102	2167	2261
Horizontal	150	0.75	0.95	0.85	0.000	0.00	0.00	0.0	0.0	0.0%	150	0	0
		Total or Average Value for All Windows.				0.49	0.45	418.2	303.6			9425	13978

10.37

Solar energy transmitted through windows for each orientation is calculated and summarized on this page, which has been simplified from the PHPP software. Window area for conductive heat loss, which includes the size of the rough opening, is distinct from glazing area which may provide solar heat gain. Note that windows on the east and north are net heat losses, while the south provides a majority of the net heat gains through the year. This is a small portion of one of dozens of pages in PHPP software.

high SHGC values. The criteria reward projects with a low surface to volume ratio in cold climates due to lower total conduction as well.

The goal of Passivhaus certification needs to be considered from the project's initial phase since massing, orientation, and glazing location are essential to meeting the standard. Many of the windows need to face within 15° of south, allowing a maximum harvest of solar energy in winter. Until a practitioner has used PHPP on several projects, early design also needs to consider how thermal bridging and airtightness will be detailed as well.

Simulation

The PHPP climate analysis uses annual and monthly weather files, focusing on averages for outdoor temperature and solar gain, plus PH-specific weather files to help calculate heating and cooling loads, available from the International Passivhaus Institute (PHIUS).

Glazing selection and sourcing are often the most challenging part of PH projects in the USA, since manufacturers do not offer the variety of quality of products available in Europe. Instead of using NFRC ratings commonly found on US products, PHPP requires window properties to be entered individually. This project used Intus triple-glazed windows from Lithuania, with an SHGC of .494, and the U-value of the frame = .1673, the U-value of the glazing = .088, and a glazing spacer Psi value of .018 Btu/hr/ft^2/°F. These combined to give a whole window U-value of .14 Btu/hour/ft^2/°F.

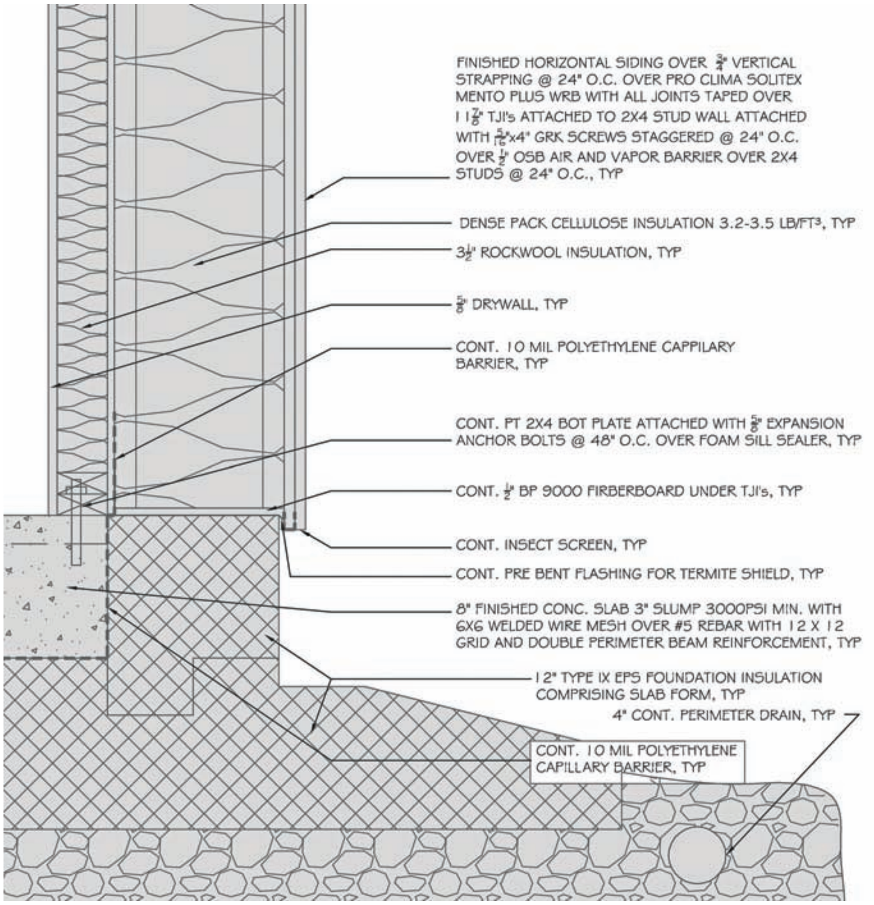
Heat transfer due to thermal bridging is estimated using THERM software to evaluate the conductance of architectural details, with each material's characteristics being considered within an overall assembly. This results in a Psi value, which is multiplied by the length of an intersection or used at a corner to estimate heat loss or gain. False colors in THERM show isothermic bands of temperatures; in the ideal envelope, the color bands are evenly spaced, meaning that insulation value is consistent throughout the detail.

All critical intersections in a Passivhaus are calculated for thermal bridging, including inside and outside corners, wall-to-wall connections, the foundation-to-wall connections, wall-to-roof connections, and window installations details. Each detail includes anything that is a known thermal bridge—bolts for balconies, cantilevered anything, framing, rafters tails, and chimneys.

As an example, the above detail shows the structural framing of the house supported on the concrete slab. Additional insulation sits over rigid insulation, eliminating the thermal bridge that often occurs at this intersection. Instead of pouring a deep foundation to prevent frost heave, the rigid insulation continues beyond the edge of the foundation, insulating the earth.

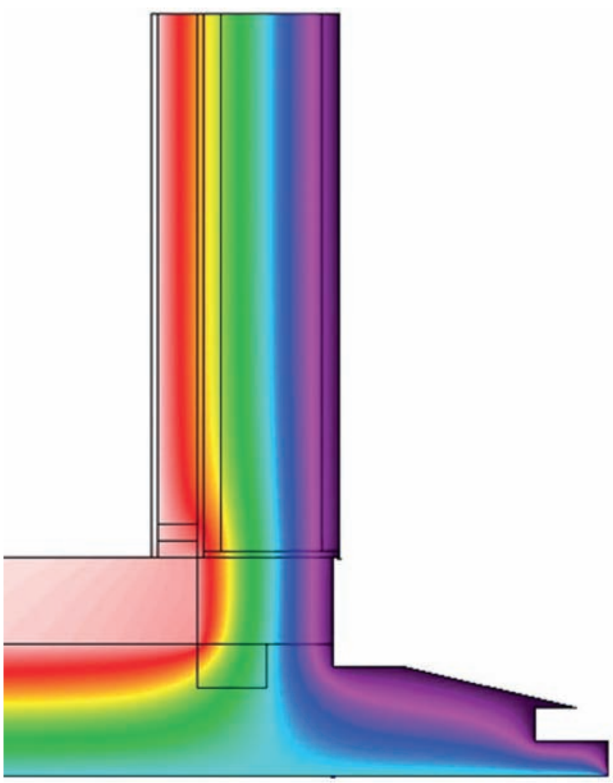
THERM software was used to verify the effective insulation value of this detail, showing the overall thermal bridging at -.020 Btu/hour/ft/°F. When this value is multiplied by the linear distance of the detail within PHPP, the expected thermal transfer is known.

The calculation rigor of PHPP has been successfully imported from Europe, with the major discrepancy being that American appliances and electrical consumption are much higher than PHPP estimates for European consumption, so care must be taken to enter appropriate energy usage for American appliances.



10.38

Footing detail to minimize thermal bridging.



10.39

THERM isothermic image of footing detail and calculation methodology.

Source: Courtesy of Chris West, Eco Houses of Vermont, LLC.

10.40

Calculation of thermal bridging effect on heat transfer.

10.41

Passivhaus compliance summary, showing predicted heating, cooling, and overall energy use. The accuracy of this software has been verified in thousands of buildings in Europe.

10.42

Energy demands.

Wall/Slab Intersection					
	U-value	Length	UL	ΔT	ULΔT
	BTU/hr·ft^2·°F	ft	BTU/hr·ft·°F	°F	BTU/hr·ft
PHPP Analysis					
wall	0.01720	5.792	0.0996	70.0	6.973166667
slab	0.01850	6.073	0.1123	35.0	3.932213542
total			0.2120		10.90538021
Therm Analysis	0.0155	8.781	0.1361	70.0	9.52765625
Thermal Bridging			-1.3777 BTU/hr·ft		
			-0.0197 BTU/hr·ft·°F		
			-0.0341 W/mK		

U-value 1 U1	0.017	Btu/hr*ft^2*F			
U-value 2 U2	0.021	Btu/hr*ft^2*F			
U factor therm	0.013	Btu/hr*ft^2*F			
Length L1	69.500	inch	5.79166667 ft		
Length L2	82.500	inch	6.875 ft		
Q 1-dim		0.188 Btu/hr*f*F			
Q 2-dim		0.168 Btu/hr*f*F			
Reduced Temperature "R"	35.6			Internal Temperature	68.0
Reduction Factor	0.60			External Temperature	23.0
				Lowest Surface Temp	66.9
Ψ_e (for PHPP)	**-0.020**	Btu/hr*f*F		**f_{RSI} at 68 °F/23 °F**	**0.98**

Energy Demands with Reference to the Treated Floor Area		
Treated Floor Area:	1140	ft^2
	Applied:	Monthly Method
Specific Space Heat Demand:	**3.11**	**kBTU/(ft^2yr)**
Pressurization Test Result:	**0.28**	**ACH_{50}**
Specific Primary Energy Demand (DHW, Heating, Cooling, Auxiliary and Household Electricity):	**32.7**	**kBTU/(ft^2yr)**
Specific Primary Energy Demand (DHW, Heating and Auxiliary Electricity):	**21.4**	**kBTU/(ft^2yr)**
Specific Primary Energy Demand Energy Conservation by Solar Electricity:	**8.6**	**kBTU/(ft^2yr)**
Heating Load:	**4.94**	**BTU/(ft^2hr)**
Frequency of Overheating:		**%**
Specific Useful Cooling Energy Demand:	**0.65**	**kBTU/(ft^2yr)**
Cooling Load:	**3.26**	**BTU/(ft^2hr)**

Chris Corson, owner of EcoCor Design/Build, described how the first few house designed using PHPP taught him to understand how the interplay of design criteria, massing, detailing, and construction affects the energy balance of a house. This understanding, accumulated over several projects, now forms the basis for all current design projects. Although the budget did not allow for data logging, the home is performing as well as was expected.

10.5 EXISTING BUILDING ENERGY ANALYSIS 1

Existing buildings require different priorities for reducing energy use than new construction. Orientation, bulk, and skin-to-core distances cannot be changed. Instead, thoughtful consideration and simulation of options can produce energy-efficient buildings with extremely low embodied energy.

Project type:
Retail to office conversion

Location:
Bremerton, Washington

Design/modeling firm:
Rice Fergus Miller/Ecotope

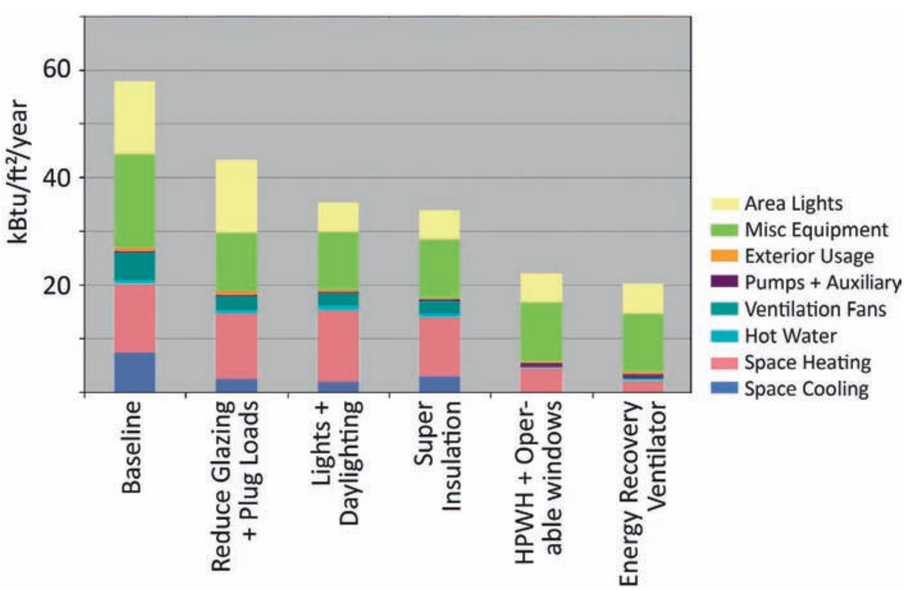
Overview

Deep green retrofits of existing or abandoned buildings present unique challenges to design and construction teams, since orientation, glazing size, and location, and other decisions, are difficult to change. However, reusing an existing building can be a very cost-effective approach to creating a high performance building.

Architecture firm and project developer Rice Fergus Miller set high goals of performance for water and energy use during an initial eco-charette. They achieved all of them for just $105 per square foot, 60% less than the cost to tear down the old structure and build a new building. Their new office was designed to be Net Zero Energy ready, meaning the installation of 160 solar panels was the only additional step necessary to achieve Net Zero Energy. The team ensured that the building's structure would carry the additional loads from future solar panels.

The architecture office occupies around 18,000 ft^2 of the 32,000 ft^2 building, with additional area being subleased on the mezzanine and retail on street, along with an existing parking garage.

The first year of occupancy, energy use tracked very close to the target EUI of 20 kbtu/sf/yr. The project team also achieved LEED Platinum (v2009, 91 points) and met the 2020 threshold of the 2030 Challenge.



10.43

Selected sustainable strategies and relative impact on various modeled energy uses.

The firm leadership realized early on that the project budget would not support incremental "green measures" and that the sustainable strategies employed needed to be completely integrated into the architectural design. In addition, the project team strove to use "off the shelf" technology to reduce costs. Load reduction through super-insulation and heat recovery strategies reduced the overall cost of the HVAC system which resulted in a no cost add for the high efficiency heat pump system. The team also designed systems to be "off" as much as possible, including the mechanical and lighting systems.

One challenge in approaching this project was that there was no example of this type of low-energy retrofit being done regionally. As with many low-energy buildings, the design team opted to include the potential for additional measures that could be installed later if necessary. For example, the central roof monitor is lined with windows on both sides. While only one bank of windows was outfitted with actuators for natural ventilation, based on simulation, both banks of windows received operable windows. While unlikely, if the space consistently overheats, the second bank of windows could be fitted with actuators.

When the project was complete, the partners asked the bank to find an appraiser with knowledge of and experience with green buildings. The LEED-accredited appraiser asked for the energy model results—by realizing ongoing operational efficiencies, she was able to put an increased value to the project, and the appraisal came in higher than anticipated. This meant the partners had greater equity in the project, which lowered their interest rate and payments.

Simulations

The goal of creating a Net Zero Energy ready building set the stage for early energy modeling. While wind energy was explored, the amount of solar energy that could be generated on the rooftop set the target EUI of 20 kBtu/ft^2/year. Working towards that goal, the energy model became an integral part of the design process, informing every decision. The overall energy reduction strategies are shown incrementally against a baseline of retrofitting to comply with the Washington State Energy Code in place at that time.

Reduced Glazing and Plug Loads

Since the existing building had very few windows, the project team was able to set a glazing percentage and then determine the ideal locations of some of the new windows. Informed by the energy model, the team determined that a glazing percentage of 30% of gross wall area was a good balance between daylight, views, and energy use.

Initially, a triple-glazed window was selected to reduce conduction losses. However, the contractor was able to find a double-glazed product that reduced cost while matching the U-value and Tvis of the triple-glazed product. The chosen windows were a specialized dual pane window with three spectrally enhanced low-e coatings on the glass, resulting in a U-value/SHGC/VT of 0.24/0.20/0.46, respectively.

Ultimately, the design of the building resulted in a "hands on" approach in regard to its energy usage. A building dashboard was brought online roughly 6 months after occupancy, and immediately revealed some heat pump installation errors. After correcting those, it became apparent that by far the largest energy loads in the building were plug loads.

During the design phase, the team had looked at plug loads and server energy use, and the firm engaged in more careful purchasing of electronics. An analysis of the data generated by the dashboard informed decisions to turn off non-essential equipment at night and increase the "sleep" function settings on plotting equipment. Power strips were installed at each workstation, and are turned off at night to eliminate power usage from computer equipment in "sleep" mode.

Lights + Daylighting

The building has a clerestory monitor that runs most of the length of the building in the north/south direction, flooding the core of the upper level with daylight. A daylighting analysis was performed early in design by the Integrated Design Lab in Seattle, and indicated that light levels at the workstations would be lower than desired. Based on subjective experiences of the light levels, the team felt the recommendation to add skylights above work areas was unnecessary. After occupancy, however, the only complaint about the space is the lack of light at the workstations in these areas.

The placement of new windows was determined using simulation, with the south face of the building being preferred for the ability to benefit from solar heat gain in the winter. Lighting power density (LPD) was reduced from code levels to 0.55 W/ft^2 with the use of side and overhead daylighting with daylighting controls.

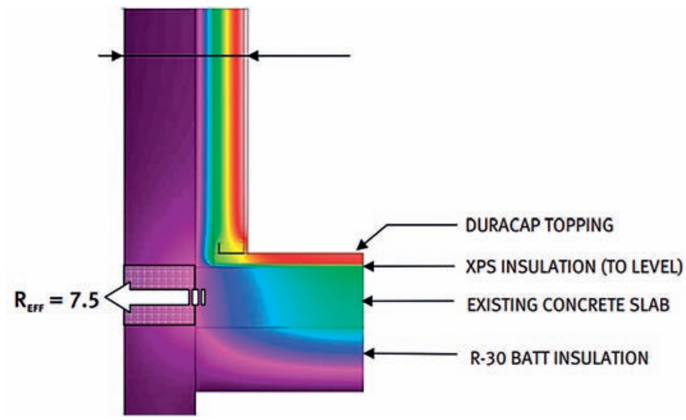
Super-insulation

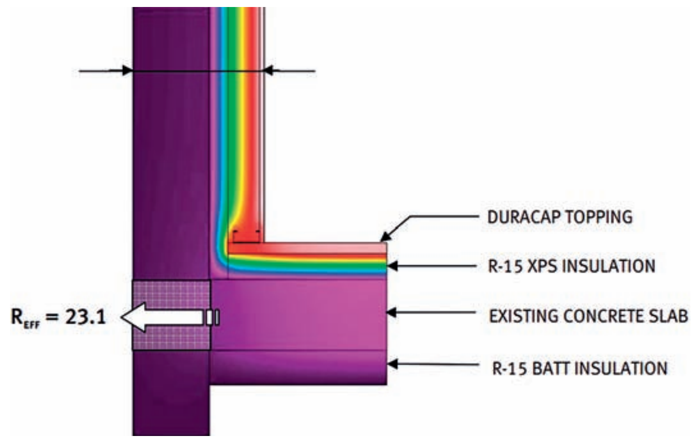
Since Bremerton is in a heating climate, the eQuest energy model indicated that a super-insulated, air-tight envelope was the first major step to achieving a low-energy building. The super-insulation strategy maintains indoor comfort for occupants since it keeps the mean radiant surface temperatures above 65°F and eliminates cold spots that cause asymmetrical discomfort.

To reduce heating energy, one of the team's goals was to construct the building so that it would maintain a minimum temperature of 62°F at night with no heating. A UA target of .1 per ft^2 was set, which allowed the design team freedom to achieve this in the most cost-effective way.

The mass, airtightness, and super-insulation meant that the heating system was primarily used to warm up the building on weekday mornings. Lights, plug loads, the server room, and people would provide most of the additional annual heating requirements. Temperature monitoring in the completed building has confirmed the energy modeling that predicted that the building would not drift below 62°F at night.

With the existing concrete shell and the requirement to frame with non-combustible materials (Type 3B), the selected wall assembly included 1.5" spray foam against the interior side of the 8" thick





10.44 and 10.45

THERM image showing thermal bridging at the slab/wall intersection. 10.46 shows a detail to eliminate the thermal bridge.

Source: Courtesy of the RDH Group.

concrete shell. A 3.5″ metal stud wall was set 7″ off of the face of the spray foam surface, with the cavity filled with a loose insulation to create an R-33 assembly with very little thermal bridging. In addition, the assembly has the thermal lag of a heavy mass wall due to the concrete on the outside of the assembly. The roof was insulated to R49, and R30 spray foam was used between the occupied floors and the parking garage below.

The team was concerned about the potential for the dew point of the wall assembly to be inside the insulation. Hygrothermic modeling of various conditions on the building indicated that the only problem area was where the concrete slab and concrete walls intersected, since the dew point was within the concrete wall otherwise.

The spray foam directly applied to the concrete also reduced the potential for infiltration. A typical building is occupied only 35% of the total hours in a year, and heating often occurs through the unoccupied hours when outdoor temperatures tend to be lower with no internal gains present to balance infiltration and conduction losses. The eQuest model was calibrated for infiltration rates by using the data from a blower door test on a similar-sized building.

10.46

The abandoned space had great light qualities, with a central roof monitor and tall ceilings.

Mechanical Systems and Natural Ventilation

The building is designed to be operated in heating, cooling, or passive mode based on the outdoor temperature. Major HVAC systems are turned off during passive mode, when outside temperatures are between 58°F and 78°F. This occurs around 45% of the year due to the high performance envelope.

The passive mode uses operable windows within the office to supply fresh air and cooling. The clerestory windows were replaced with operable windows, also tied in to the comfort system to provide exhaust airflow. A 14′ diameter fan was placed at the top of the opening to reduce thermal stratification, maintaining air temperatures within 2 degrees between the upper and lower levels.

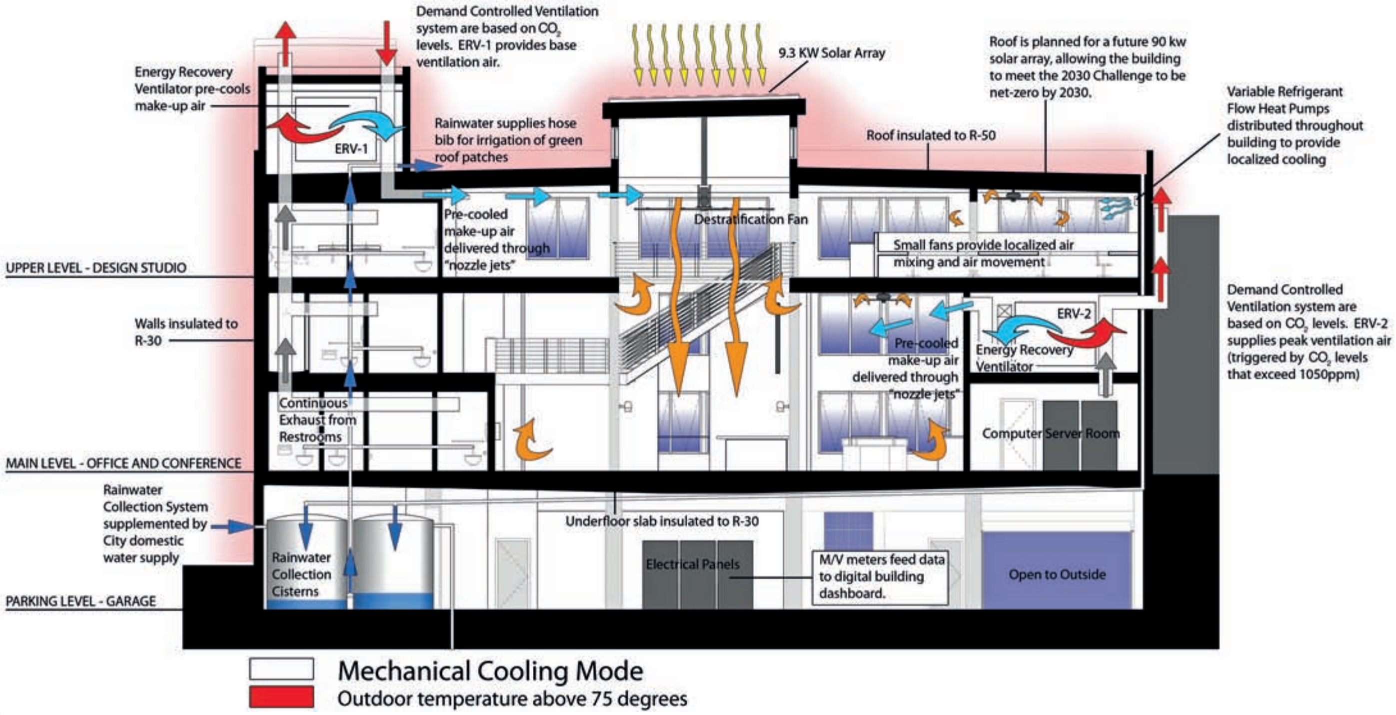
Below 58°F, windows close, the energy recovery ventilator (ERV) turns on to recycle heat from exhausted air, and the heat pump switches to heating mode. Above 78°F, the ERV also turns on, with the heat pump in cooling mode. Since the building is so well insulated, simultaneous heating and cooling with the mechanical system are not necessary.

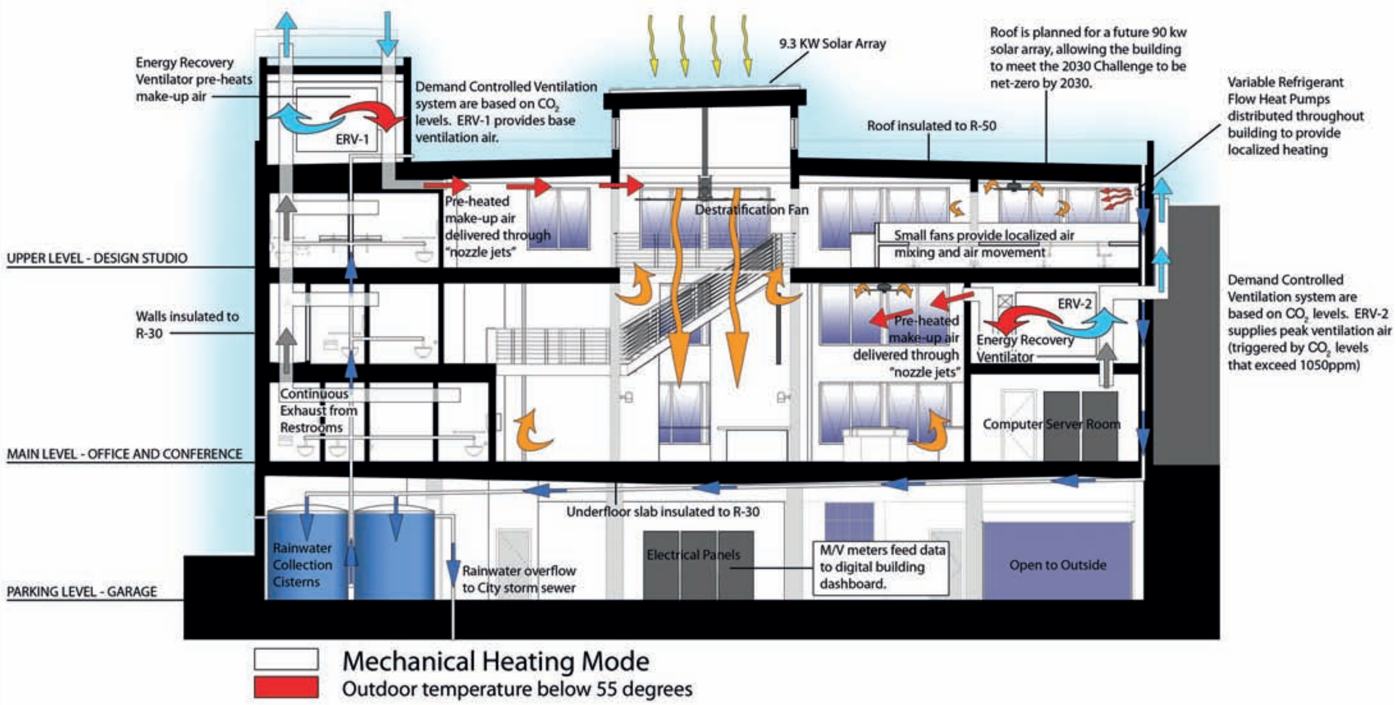
One of the most striking design moves was to cut an 18′ x 25′ opening in the upper floor. This allowed daylight from the clerestory to reach the lower level, helped visually connect the spaces and allowed the stack effect to work as part of the ventilation strategy in all three operational modes.

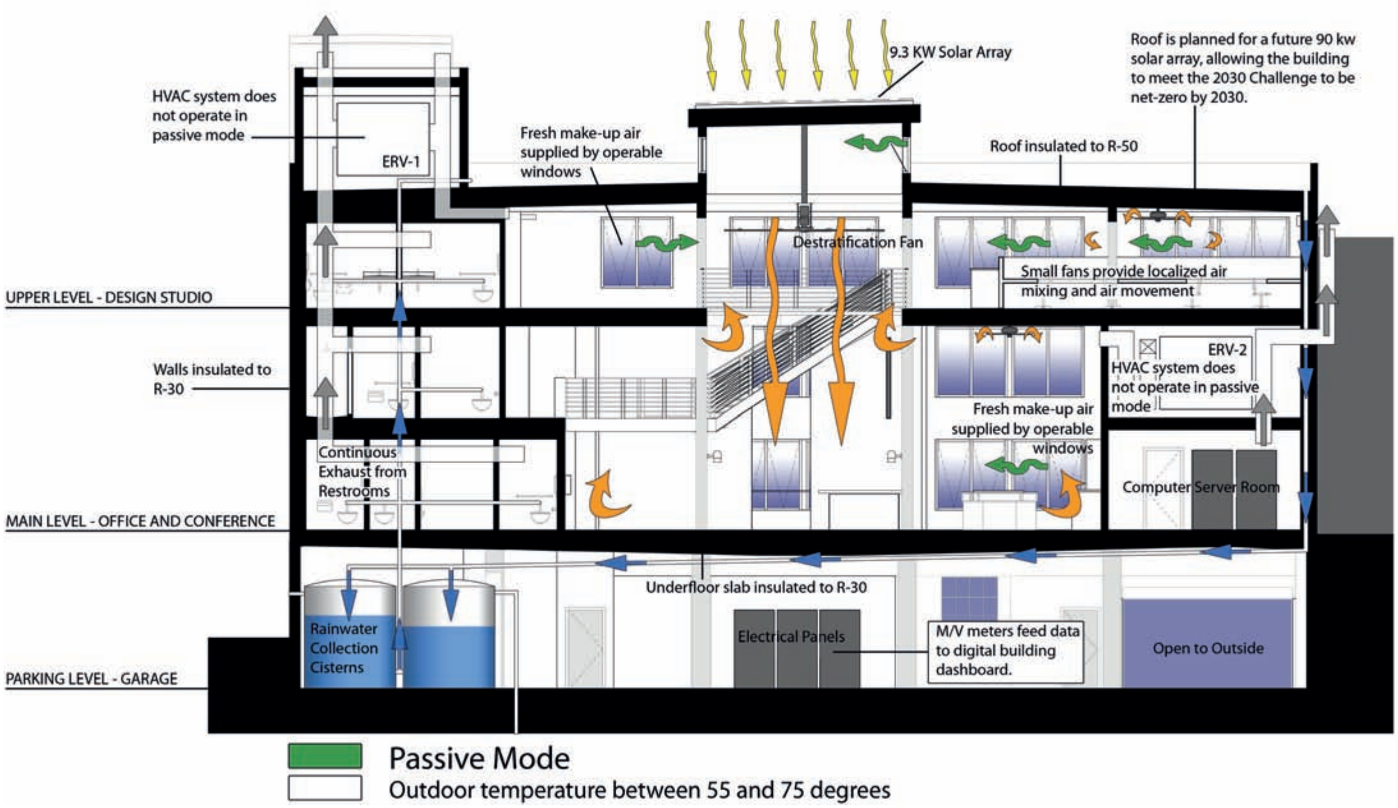
With building loads reduced significantly due to the above measures, efficient, premium mechanical systems became affordable. Instead of heating and cooling loads in the typical range of 400 ft^2/ton of cooling, loads were reduced to 850 ft^2/ton. A Variable Refrigerant Flow mechanical system was chosen, costing only $10 per ft^2 due to the great passive design measures. It works with all three operational modes, and works efficiently down to nearly 0°F.

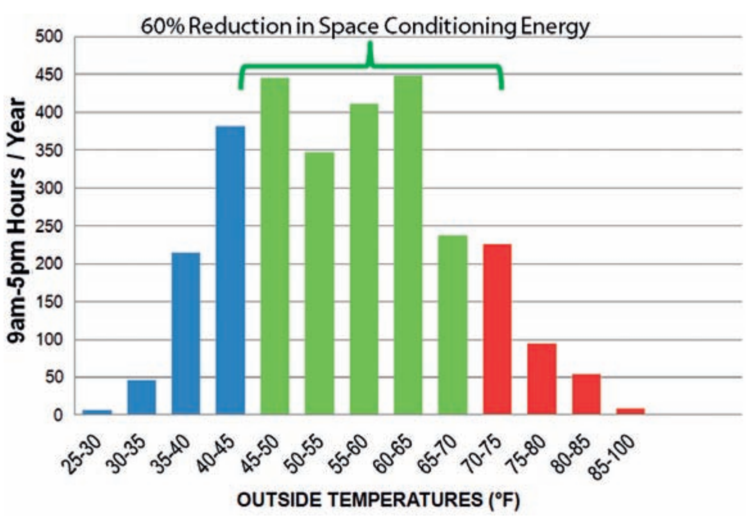
10.47a, 10.47b and 10.47c

Cooling, heating and passive modes.



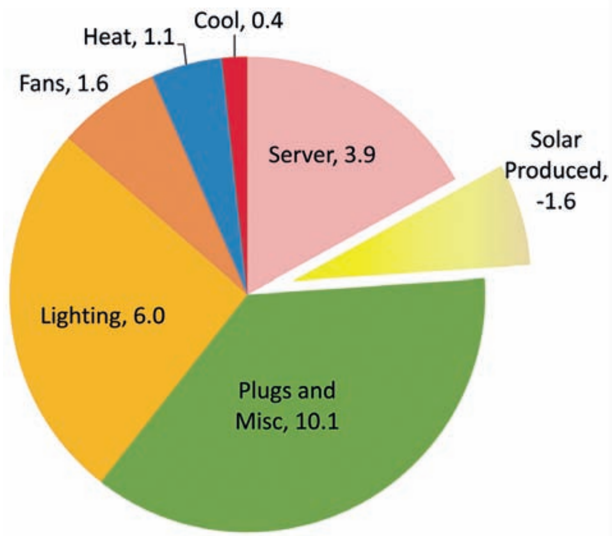






10.48

Temperature bin chart showing in green temperatures that require no mechanical heating or cooling.



10.49

Energy end uses.

10.6 EXISTING BUILDING ENERGY ANALYSIS 2

Project type:
Existing office building

Location:
Newport Beach, California

Design/modeling firm:
Callison/KEMA Energy Analysts

A low-energy building requires early goals, full project team interaction throughout the process, and a variety of simulation types employed at various stages of the project to ensure success.

Overview

For DPR Construction's major remodel of their newly-leased office space in Newport Beach, energy goals were set at the project kick-off eco-charette. While Net Zero Energy was targeted, several site constraints limited the team's ability to achieve it. The resulting design, which balanced energy performance, the landlord's desire for minimally visible modifications to the exterior, re-use of the existing mechanical system, and a reasonable cost, performs around 35 kBtu/ft^2/year, which is 67% lower than the previous tenant in the space, and 58% lower than California's stringent title 24 baseline. This was accomplished with a return on investment within the 9-year lease.

The project team met regularly to discuss ideas about energy use. One team member later commented that establishing energy goals early smoothed the workflow because only the most energy-efficient options needed to be studied. Also, having a designated energy analyst and champion (KEMA) ensured that energy impacts of decisions were always "on the table" in team meetings. With solar panels being added in 2013, the project expects to reduce energy use by another 25%.

Simulations

Early in design, the team assessed daylighting potential within the existing geometry and window sizes, locations, and properties. The simulations show false colors for areas above 25fc, and are clipped to omit colors in areas below this threshold. The simulations showed that the existing shell could comply with LEED credits. The team felt, however, that to create a well-lit and balanced feeling in the space, some electric lighting would be used for the majority of the occupied hours.

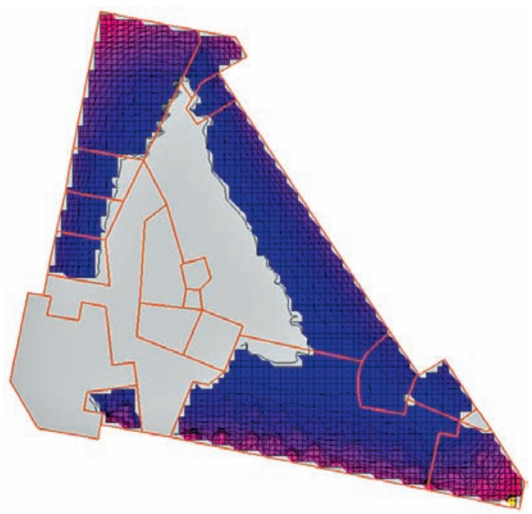
While daylight tubes had been used at other DPR offices, since this space is on the lower floor of a building, tubes were not possible. For this reason, the lighting design focused on high efficiency LED fixtures controlled by each user. Instead of uplighting the space with a continuous white ceiling, dropped ceilings with downlights were arranged in groups, with space between them for large fans to circulate air, or for air to stratify at other times.

The team also pursued shading strategies to minimize cooling loads, but the team felt the aesthetic impact would not have been approved by the landlord.

For DPR's first Net Zero Energy renovated office build-out in San Diego, the team learned that plug loads were much higher than anticipated during design. To control plug loads in this and other offices, a kill switch was used at each workstation to eliminate plug loads during unoccupied hours.

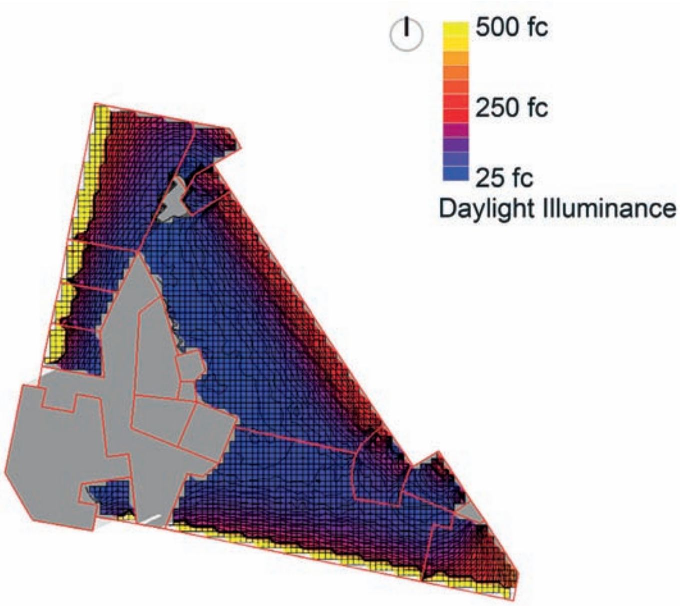
Natural Ventilation

In addition to high-performance lighting, the other game-changing strategy was the introduction of natural ventilation. Since the Variable Air Volume HVAC system was in place prior to leasing, this system could not be replaced or modified significantly. This meant that the team could not take full advantage of a mechanical system specifically designed to accompany the strategies that reduced the cooling load.



10.50

Daylighting simulation, illuminance levels, Sept. 21 at 9 a.m.



10.51

Daylighting simulation, illuminance levels, Sept. 21 at 3 p.m.

Instead, the team looked for ways to limit use of the mechanical system through passive technologies. The resulting design reduced the annual HVAC cooling energy use by an average of 64% across different spaces.

To ensure natural ventilation would continuously flow through the building, especially during peak cooling times, an exterior CFD model was used to estimate differential wind pressures at the various building façades, see Case Study 9.4. Later on, a bulk airflow model using DesignBuilder was used to determine where windows should be located to supply enough cooling breezes to maintain comfort using natural ventilation.

Once natural ventilation became a primary energy reduction strategy, the project team began redesigning the interior. Every element of the new interior design began supporting natural ventilation by allowing unobstructed airflow paths through the space.

The open office plan was now designed with high ceilings, discontinuous dropped ceilings to reflect light, and low partition heights. Areas that required some visual screening were designed with open areas to provide some separation while not impeding airflow.

Areas that required more privacy were located where cross-ventilation was not possible, such as at the deepest portion of the building where the bathrooms are located. Rooms with negative air pressure, such as bathrooms and copy rooms, were located in deemed air path dead zones, designed to assist in creating airflow to areas which otherwise would not be well supported by the natural ventilation system. Conference rooms were placed so that cross-ventilation could be achieved without opening them up to the rest of the office during private meetings. A central enclosed area was curved to reduce air resistance and provides a symbol of the natural ventilation aesthetic.

The landlord required that the addition of operable windows had to be minimally visible and integrated with the existing architecture. The design team proposed operable, internally-framed windows which would be barely noticeable when closed, along with a validation of potential energy and cost savings from the building performance model. The landlord agreed to the proposal, partially based on the energy performance, allowing the natural ventilation strategy to proceed.

10.52

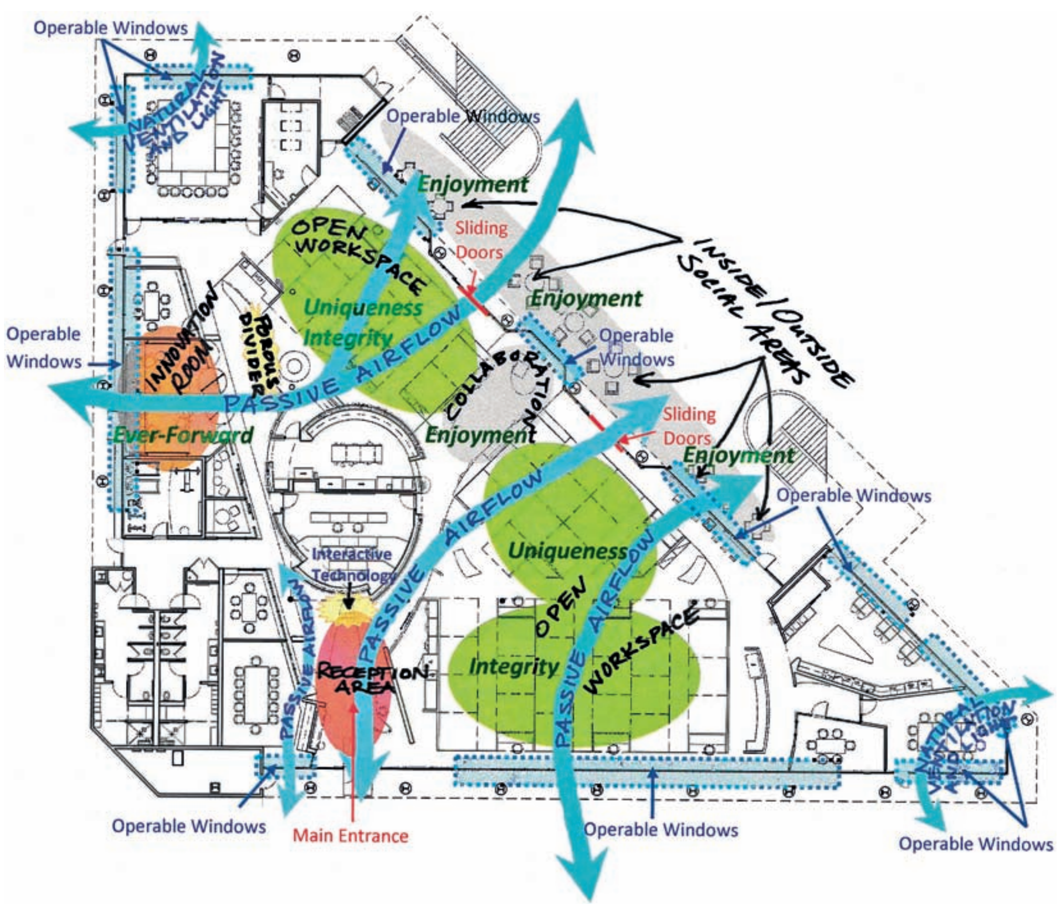
DPR's open office plan has non-continuous dropped ceilings that allow airflow and large fans to provide comfortable conditions.

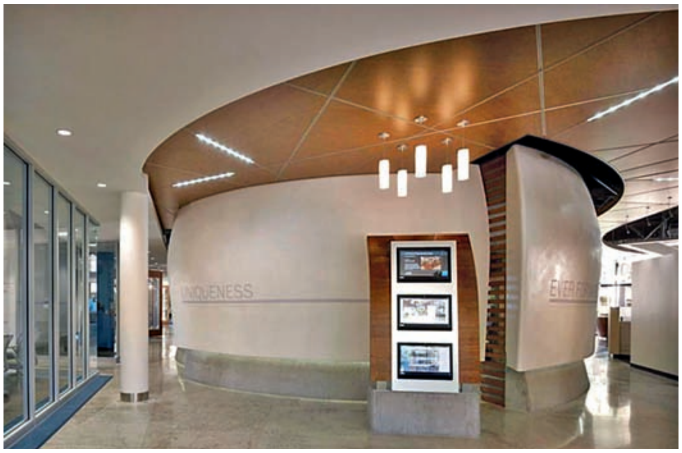
Source: Courtesy of Callison and KEMA.

10.53

Floor plan diagram after integration of airflow strategies.

Source: Courtesy of Callison and KEMA.





10.54

A central space that required privacy was curved to promote airflow through the office, and provide a symbol of the design intent.

Source: Courtesy of Callison and KEMA.

10.55

The landlord was concerned about any visible changes to the façade. Operable windows added as part of this major remodel were chosen to have minimal visibility from the outside when closed.

Source: Courtesy of Callison and KEMA.

Comfort

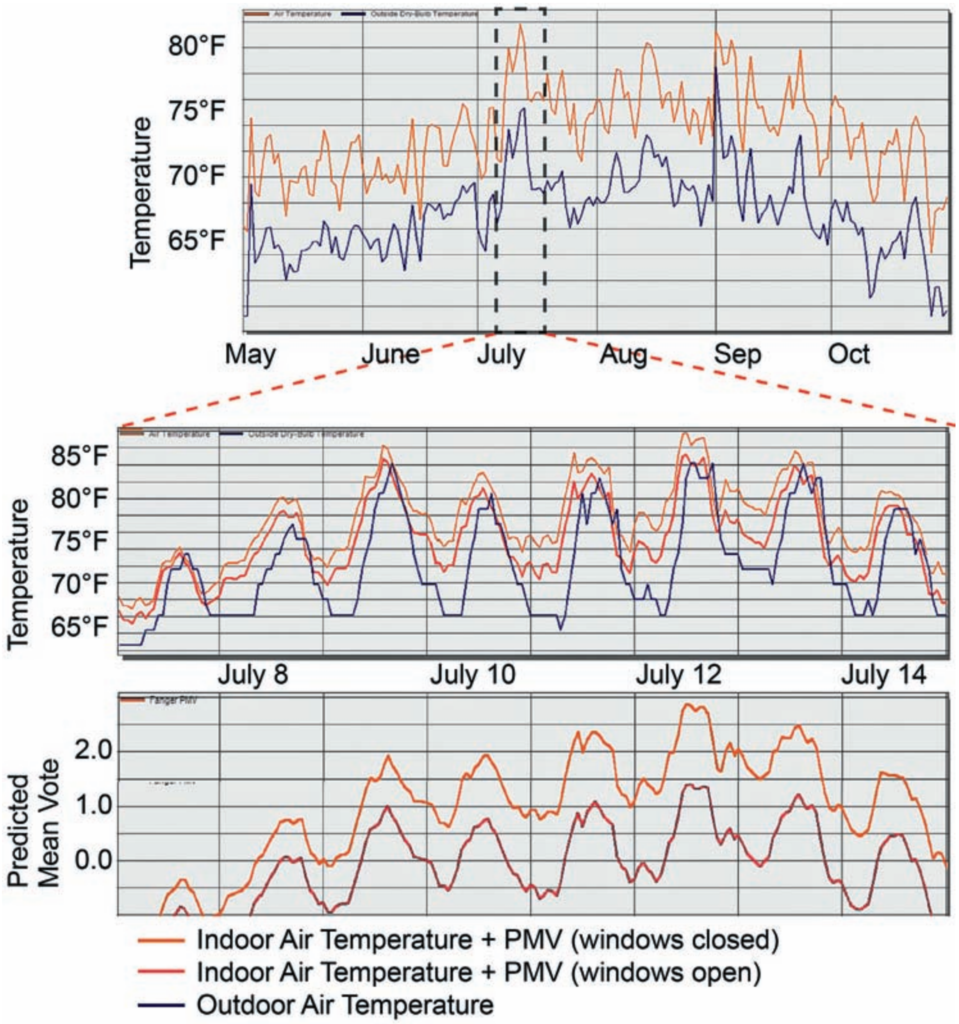
Since DPR would have to pay for the cost of any operable windows to be added for natural ventilation, the number of operable windows needed to be minimized. To maintain ASHRAE 55's PMV comfort conditions, with temperatures between 68°F and 75°F, the energy model predicted that 20% of the façade would need to be operable. Reducing the number of windows required discussions about the interior comfort parameters that DPR preferred. It also led to the elimination of window screens, which impeded airflow.

The discussion on comfort was partially informed by DPR's successful Net Zero offices in San Diego, designed by the same project team. There, the space was designed for an 81°F maximum temperature level. DPR, however, allowed the maximum temperature to slowly rise over the first year of occupancy. Since there were no complaints, they realized that temperatures up to 83°F were comfortable. In fact, temperatures up to 86°F have been recorded without complaints.

This experience, along with additional research, allowed the client to expand the design comfort range for the Newport Beach offices up to 83°F. This reduced the necessary operable window threshold to 10%, saving money and making the landlord feel more comfortable with the modifications.

Conclusion

Successfully creating a low-energy design within an existing shell without significantly modifying the exterior or the mechanical system required a great team and continual validation of the proposed design with simulation. Since DPR operates other Net Zero offices designed by the same project team, first-hand knowledge of sustainability principles were also influential.



10.56

Simulated internal temperature cycles shown over several days. The peak cooling time is shown here with internal temperatures reaching the mid-80s °F for a few hours on peak days in July. The lower chart shows PMV based on the interior conditions.

Source: Courtesy of Callison and KEMA.

10.7 NET ZERO ENERGY TRIAGE

Energy reduction strategies are often interdependent. Reducing peak loads may allow the use of natural ventilation or radiant panels, for example, which operate with little or no energy and reduce annual energy use.

Project type:
6-story office building

Location:
Seattle, Washington

Design/modeling firms:
Miller Hull/PAE Consulting Engineers/University of Washington IDL

Overview

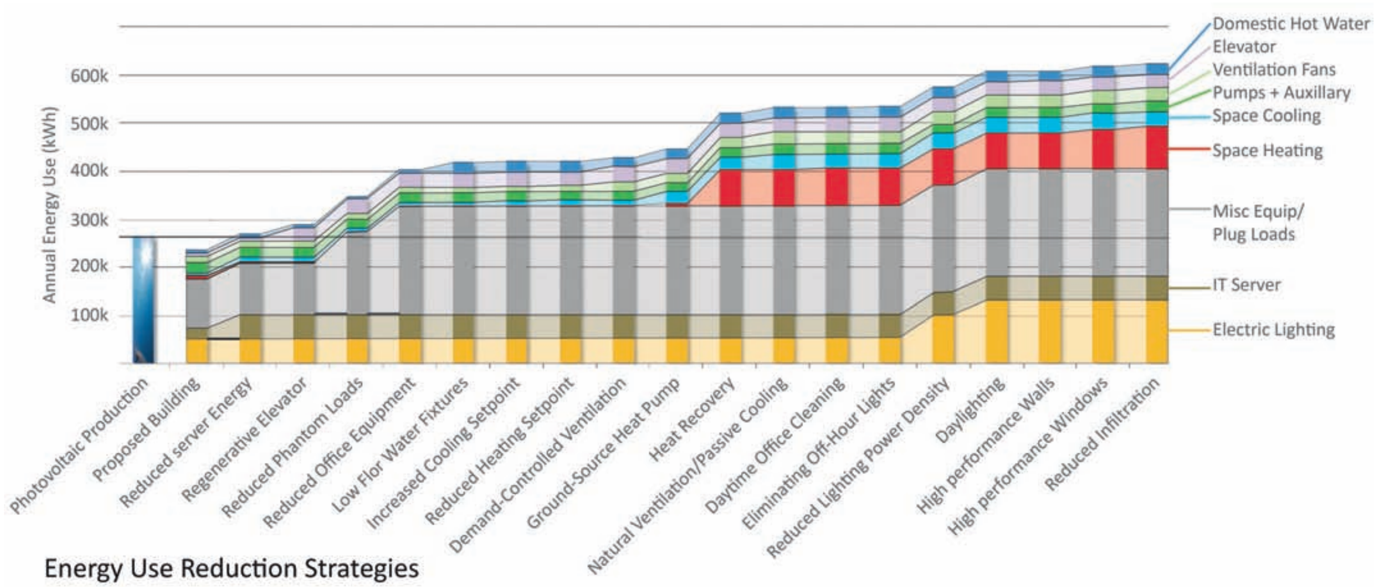
The Bullitt Center is a speculative office building that will house the Bullitt Foundation and other tenants. It is designed to achieve Living Building Challenge (LBC) status, including Net Zero Energy (NZE), plus Net Zero water, waste, and other LBC goals.

The development of the first speculative Living Building required more than the usual amount of time to research and design forms, systems, and materials that would comply with the Living Building Challenge, so the soft costs were higher than for a normal building. The construction cost, around $350/ft^2, which includes the cost of photovoltaics and significant infrastructure improvements required by the city, is within the typical realm of a Class A office in Seattle's downtown core. The Bullitt Foundation (grant provider for deep green research and projects) has been transparent in sharing the detailed research and analysis required to design and construct a Living Building, and will continue to provide information on project performance once the project is occupied.

With ambitious goals, this project required an integrated team approach. The architect, engineer, and other consultants and subject matter experts worked together from project kick-off through

10.57

View from southwest.



10.58

Energy use reduction strategies.

construction to ensure success. This allowed formal and informal dialogues within the design team that considered comfort, site planning, glazing, solar control, daylighting and glare, and natural ventilation on the path to Net Zero Energy use.

Figure 10.59 shows how each strategy's energy reductions helped reduce overall energy use. While some strategies may not seem to contribute significantly, such as glazing or daylighting, their effects permit other strategies, such as natural ventilation or radiant cooling, that do reduce energy use. Only by considering all of them simultaneously did the Bullitt Center achieve its zero energy goals.

Seattle is located in a fairly mild climate and has a very strict energy code, meaning that code-minimum buildings in this area are less energy-intensive than in many other regions. It also means that improvements beyond the code require more thoughtful and integrated design.

Simulation

One of the early studies looked at establishing an energy budget by assessing potential on-site energy generation using a photovoltaic (PV) array, covered in Case Study 7.5. This gave the team a goal of 16 kBtu/ft^2, which challenged them to rethink many building norms to eliminate unnecessary energy use.

Massing and Façades

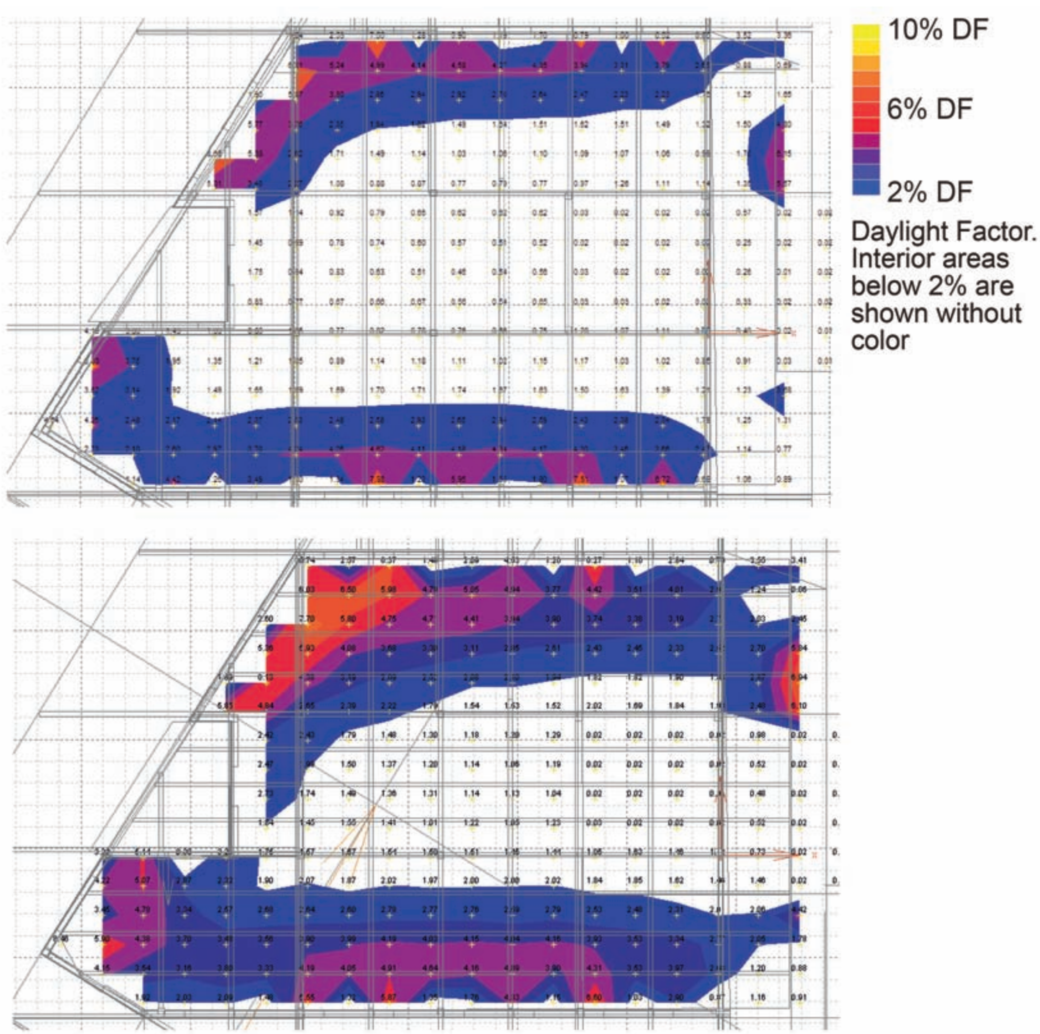
The best and most cost-efficient option within the site zoning and height allowances was to minimize the skin-to-core distance and maximize the ceiling height, with a final floor-to-floor height of 13′10″. The Center received a height bonus from the City of Seattle after showing that achieving daylighting requirements in the LBC was nearly impossible without it. This used daylighting studies prepared by Miller Hull using Ecotect with Radiance as the calculation engine. This effort was supported by the University of Washington Integrated Design Laboratory (UW IDL).

High performance windows were chosen during a lengthy research process. Windows needed to be operable for natural ventilation, achieve an overall U-value of 0.25 to reduce heating loads, and include a high Tvis of 60% for good daylighting design. The system that best met the needs of the project was a high performance curtainwall by German company Schuco that was designed to accept triple glazing. The product was being introduced to the Pacific Northwest by a local glazing contractor and intended for local manufacture.

Opaque walls were insulated with R-19 stud cavity insulation and 3½ inches of exterior insulation installed with a thermal cladding support system, allowing an effective assembly R value of 22. Since Seattle already required R-18, the difference due to increased insulation alone was minimal, though

10.59

High-performance operable windows used in the Bullitt Center, combined with floor-to-floor heights of 13′10″ allow plenty of airflow and daylight throughout the space.



10.60

Floor plans showing Daylight Factor at various floor-to-floor heights at levels 3–5. 11′6″ floor-to-floor height 23% of floor has Daylight Factor > 2% (above); 14′2″ floor-to-floor height 65% of floor has Daylight Factor > 2% (below). Final floor-to-floor height was 13′10″.

combining it with the windows selection it reduced the cost of the comfort systems, such as ground-source heat pump (GSHP), Radiant cooling and heating, and heat recovery ventilators (HRV).

The Bullitt Center was designed to meet a pressurization test of .24 cfm/ft^2 of façade @ 75 Pascals. The testing measured the leakage rate at .19 cfm/ft^2 of exterior wall area.

Daylighting

Daylighting drove the early design process. An initial design located an unheated atrium in the center of the project to allow daylight while maximizing the buildable area. Since the Center is located on a tight urban site, this allowed only a small atrium. The atrium was partially covered by the light-blocking photovoltaic (PV) array, reducing light, and the cost of additional high-performance glazing to create the atrium quickly removed it from consideration.

Miller Hull studied daylight factor and point-in-time illuminance levels using physical models, plus primarily Ecotect and Radiance to further optimize daylighting decisions around fenestration quantity and configuration, glazing transmittance, shading strategies, and interior surface configuration and reflectivity. The IDL was a critical resource during this work to determine optimum layouts within the building.

The ultra-low lighting power density of 0.40 W/ft^2 included a conceptual design that relied primarily on workstation-based task/ambient lighting systems with a high level of local control.

During the detailed energy modeling process in design development, Chris Meek of the University of Washington Integrated Design Lab (IDL) worked with Marc Brune of PAE Engineering to determine the optimum method of predicting the lighting use factor (LUF). They compared the predicted lighting levels from the more detailed model from the IDL with the eQuest model, finding that the front zone was over-predicting lighting levels while the back zone tended to under-predict light levels.

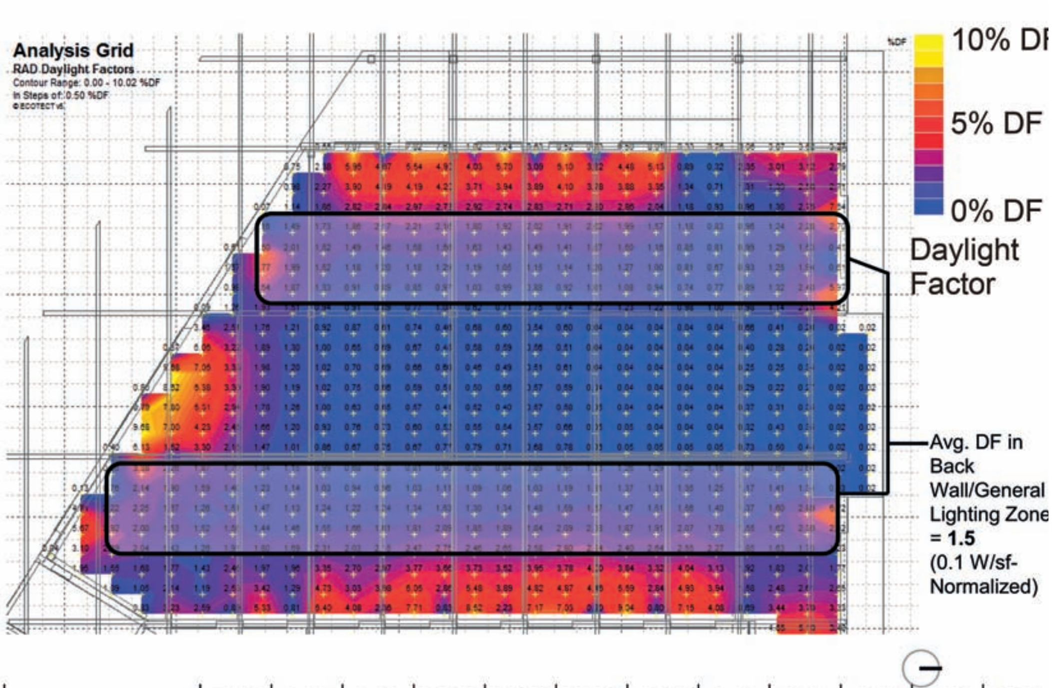
Instead of overriding the energy model's lighting calculations with the IDL's results, PAE used them to calibrate the eQuest model so it would mimic the IDL's results. This meant that as geometry or window selection changed, the results would be automatically updated as well, leading to a much smoother workflow.

Glare was avoided due to automatic exterior blinds on floors 3–5, while the PV array shades the 6th floor. The lower floors have operable interior blinds for glare control.

Reducing lighting energy use meant installing occupant sensors throughout, and designing for all lighting to be off at night while the building is unoccupied. Having the primary stair located on the outside wall allowed daylighting to eliminate most daytime lighting use. Shifting office cleaning to the daytime reduced both the lighting loads and the potential for the cleaners to leave lights on all night.

Mechanical Systems and Natural Ventilation

While natural ventilation does not seem to reduce energy use much, the cooling system was already very efficient and the energy effects in the chart are fairly conservative since the main energy engine, DOE-2, is not great at predicting energy savings due to natural ventilation.



	7.00	8.00	9.00	10.00	11.00	12.00	1PM	2.00	3.00	4.00	5.00	6.00
JANUARY	0.40	0.34	0.28	0.25	0.23	0.23	0.23	0.25	0.28	0.34	0.40	0.40
FEBRUARY	0.37	0.29	0.24	0.20	0.19	0.18	0.19	0.20	0.24	0.29	0.37	0.40
MARCH	0.29	0.24	0.19	0.17	0.15	0.14	0.15	0.17	0.19	0.24	0.29	0.40
APRIL	0.25	0.19	0.16	0.14	0.13	0.13	0.13	0.14	0.16	0.19	0.25	0.30
MAY	0.21	0.17	0.14	0.13	0.12	0.12	0.12	0.13	0.14	0.17	0.21	0.27
JUNE	0.20	0.16	0.14	0.13	0.12	0.11	0.12	0.13	0.14	0.16	0.20	0.26
JULY	0.21	0.17	0.14	0.13	0.12	0.12	0.12	0.13	0.14	0.17	0.21	0.27
AUGUST	0.25	0.19	0.16	0.14	0.13	0.13	0.13	0.14	0.16	0.19	0.25	0.30
SEPTEMBER	0.29	0.24	0.19	0.17	0.15	0.14	0.15	0.17	0.19	0.24	0.29	0.39
OCTOBER	0.37	0.29	0.25	0.21	0.19	0.18	0.19	0.21	0.25	0.29	0.37	0.40
NOVEMBER	0.40	0.34	0.28	0.25	0.23	0.23	0.23	0.25	0.28	0.34	0.40	0.40
DECEMBER	0.40	0.38	0.30	0.27	0.25	0.25	0.25	0.27	0.30	0.38	0.40	0.40

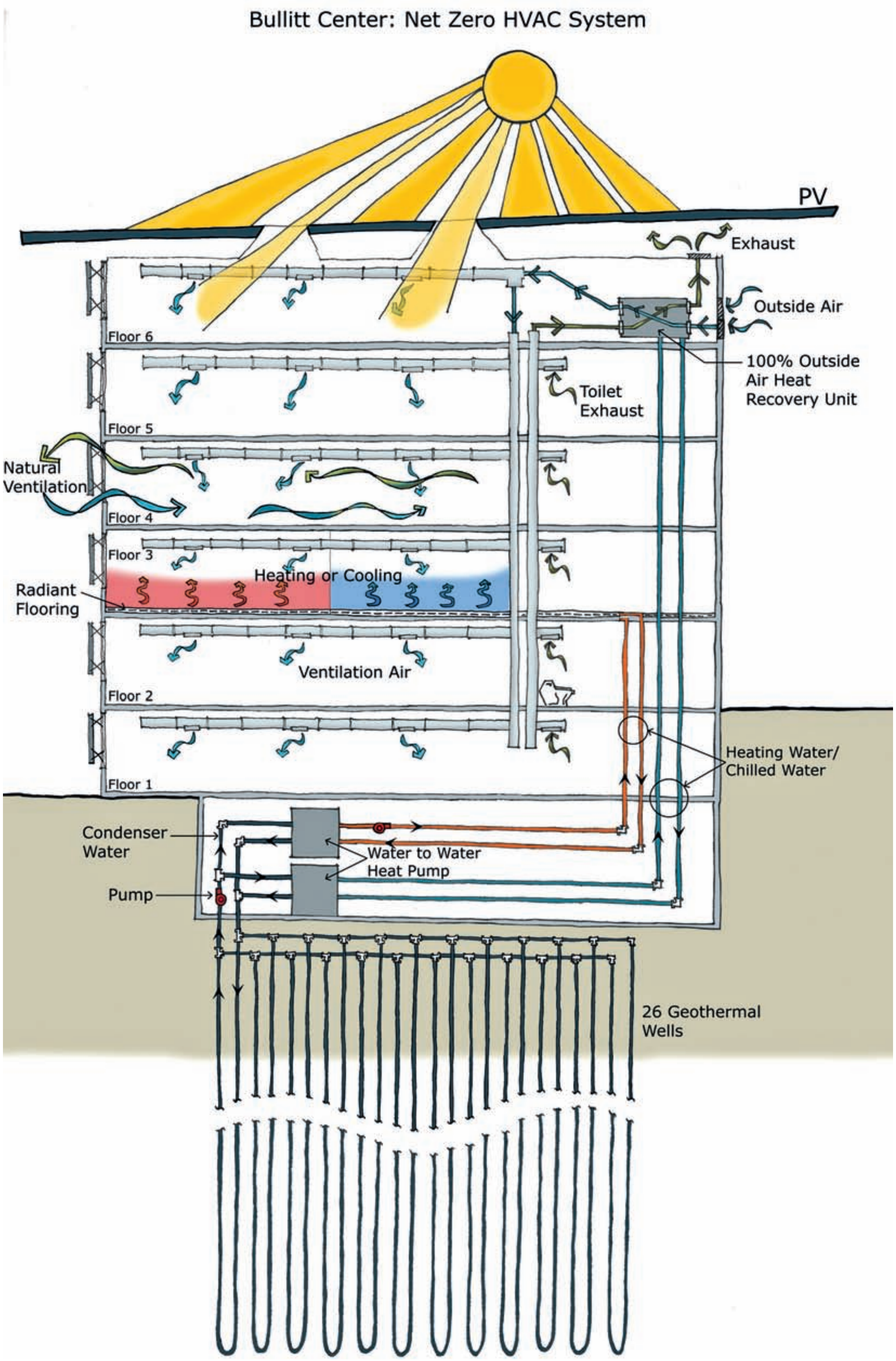
10.61

Daylight study showing estimated lighting use for each hour during each month in the highlighted daylight zones, in Watts/ft^2. The upper graphic is an Autodesk Ecotect output of a Radiance analysis.

The airflow simulations were done using the TAS engine and exporting to eQuest, using the same geometry and zoning as the Revit and energy models for consistency. Airflow analysis for the Bullitt Center is covered in more detail in Case Study 9.3.

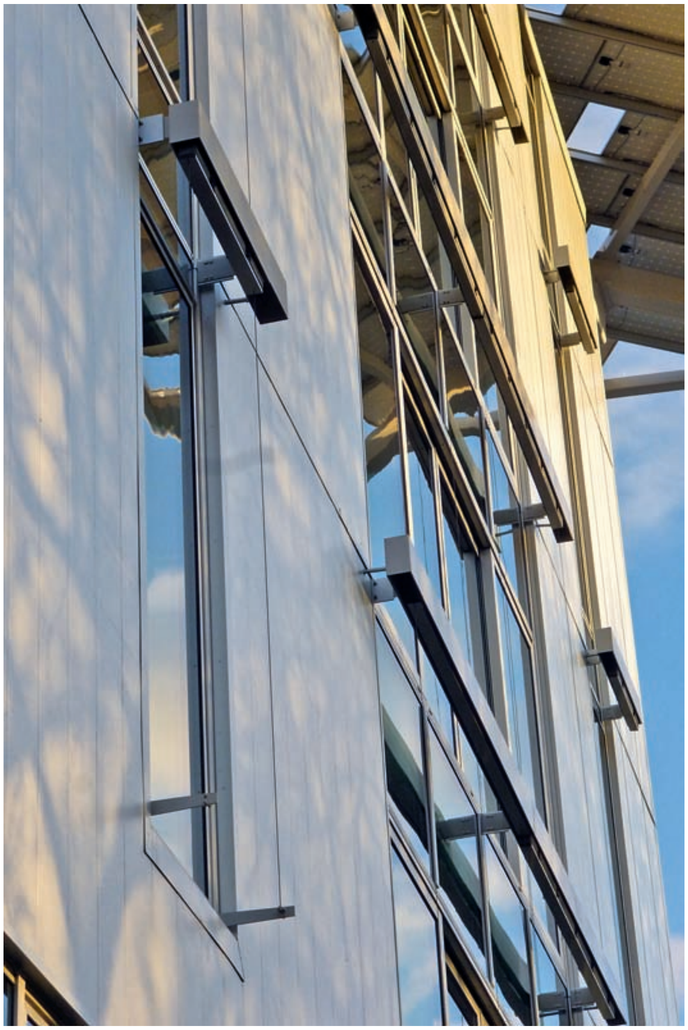
A heat recovery ventilator (HRV) transfers energy from exhausted air to incoming air, though the air streams do not mix. They are part of most low-energy buildings and all Passivhaus projects to reduce heating and cooling savings. An energy wheel was selected for the Bullitt Center, allowing the heat generated by people, lights, and equipment to stay within the building during the heating season.

A ground source heat pump (GSHP) exchanges energy with the ground to provide heating and cooling with 330% and 600% coefficient of performance (COP), respectively. Twenty-six wells were drilled 400′ deep, and spaced around 15′ apart, though each was located to avoid footings and other obstructions. All the wells were located under the building in the west half of the site so they could be drilled during the excavation and construction of the basement on the east half while maintaining the construction schedule. The considerably-downsized wellfield was a result of the generally low building heating and cooling loads.



10.62

Energy systems diagram, showing photovoltaics on the roof, natural ventilation, radiant slab heating, mechanical cooling, and integration with ground source heat pump.



10.63

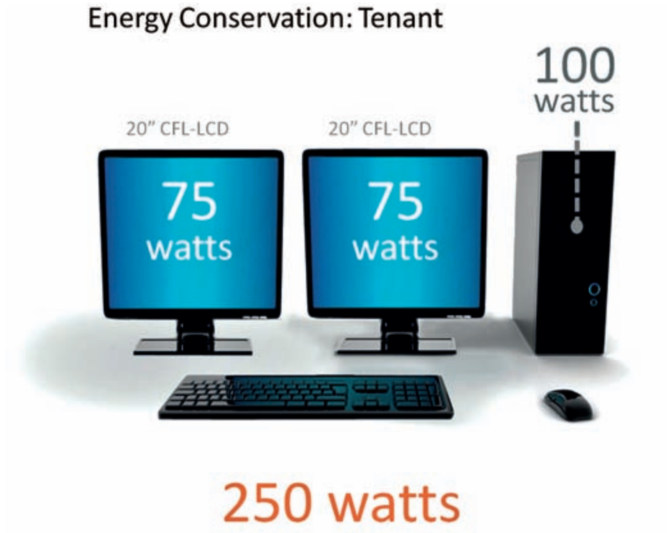
Automated external operable shades on guide wires control heat gain and glare much more effectively than internal blinds.

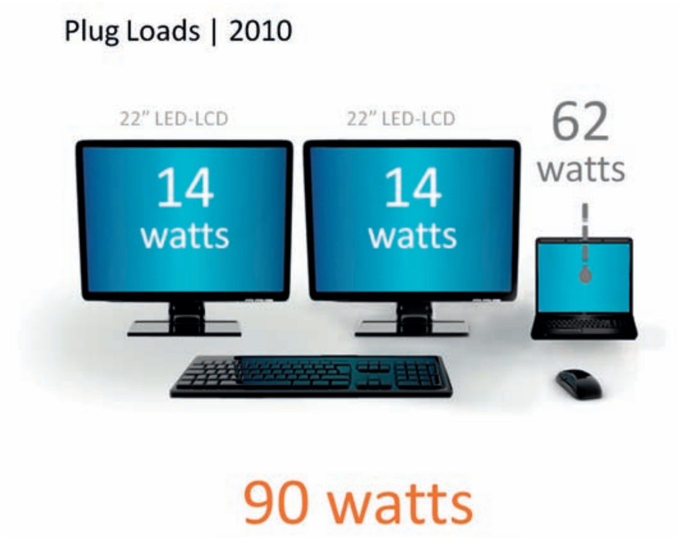
Source: Photograph © Kjell Anderson.

Adjusting the idea of comfort, via thermostat set points, can have a profound effect on energy use; for this project the set-points were 68°F for heating and 80°F for cooling instead of the more usual 72°F for heating and 76°F for cooling. Comfort during natural ventilation periods for the Bullitt Center is covered in Case Study 9.3. Demand-controlled ventilation, using CO_2 sensors to determine ventilation requirements, reduced unnecessary air heating and cooling throughout the year.

Reducing water flow through plumbing fixtures reduced energy for water heating as well. Water heating energy was further reduced by extracting heat from the GSHP thermal loop, which includes waste heat from the server room and other areas.

Reducing the electric process loads—plug loads, IT server, elevator, and phantom loads—were considered very early in the process as absolutely necessary to achieve Net Zero Energy design. The team's occupancy estimation was based on 150 sf/person, which translated into a number of occupants with a computer workstation. Based on experience, a typical workstation from 2008 used around 250W of power; for the Bullitt Center, this was reduced to 42W per workstation. While these reduced the internal heat and increased heating loads, the Comfort systems and GSHP were efficient enough to more than offset this use.





10.64a, 10.64b, 10.64c

Reducing the plug-load.

Source: Courtesy of Miller Hull and PAE Consulting Engineers.

Conclusion

- A successful combination of measures achieved drastic energy reductions enabling Net Zero operation.
- Two-thirds of the energy savings beyond the code are from operational changes and steps that will be taken by occupants to reduce energy use. This is a result of a strong code baseline, and also highlights the importance of plug loads in a non-residential building.
- The modeling began in pre-design, and was developed along with the design through the middle of CDs. The importance of the early work to the project cannot be overstated enough. The ability to continue this work into the DD/CD phase was critical in being able to support ongoing detailed design decisions.
- The obvious commitment and inspiration provided by the owner, along with the support of all the team members, were essential to the successes that have been achieved so far. We look forward to learning from the project as it moves into the inhabitation phase.

11
Software and Accuracy

Tools do not supplant skill and knowledge.
—Jason McLennan

The software systems that architects can choose from today are built on research and validation from the last 40 years of computer-based energy modeling experience. Over this period, the methods and accuracy of energy modeling have continually been improved. Until recently, this software was used only by specialists, so user interfaces were rudimentary and took months or years to learn.

The new batch of user-friendly software allows mainstream use of design simulation by non-specialists, including architects. Today's software builds on Dr. Andrew Marsh's approach in creating Ecotect, combining a fairly intuitive graphical user interface, a wide variety of simulation types, a choice of 3D modeling programs to create geometry, graphical outputs that are mapped onto a 3D model, and default values that make setting up a model for quick analysis much easier.

This chapter provides an overview of available software and the most important aspects when selecting one to learn and use, and then discusses the accuracy and validation within practice. The choice of design simulation software is unique to each firm, and the options need to be tested to ensure compatibility with each firm's workflow.

Caution is advised when architects are learning to use software to help make design decisions. While intuitive interfaces allow non-specialists to set up and run simulations, results should always be validated against the simulator's understanding of building science. The first few projects should be done as test cases while the team learns to use the design simulation process.

THE DEVELOPMENT OF GRAPHICAL SIMULATION SOFTWARE

Energy modeling grew out of the engineering professions as a method to size mechanical systems and ductwork and estimate energy loads. It became a separate profession due to the complexity of energy uses in modern buildings and the resulting complexity of modeling energy use. The ability to more accurately evaluate energy use has improved as the design–construction–operation cycle has validated energy modeling techniques, detailed research and with continually increasing computer processor speed advancements.

As the profession of energy modeling has become more specialized, architects' understanding of comfort and energy use within their buildings declined. Both the inexpensive monetary cost of energy and the level of detail required to operate and understand energy modeling have contributed to this decline.

As complex algorithms, tables, and charts are further embedded in software, the use of design simulation has begun to appeal to non-specialists such as architects. Ecotect software, created by architect Dr. Andrew Marsh and purchased by Autodesk in 2008, began a revolution in user interfaces and analysis types that has set the stage for contemporary early-phase design simulation.

The uptake among architects and revolution in graphical outputs attributable to Ecotect is undeniable, as all firms interviewed for this book use or have used it. It allows fairly simple models to be run with compelling graphical outputs that are easier to interpret and act on by architects than other software. It also includes a wide variety of analysis types such as daylighting, acoustics, solar path analysis, climate analysis, insolation, and simple energy modeling.

Since Ecotect transitioned to Autodesk and is no longer being updated, this book looks towards the post-Ecotect landscape. For the first time, several companies are creating and marketing software to the broad spectrum of architectural users.

DESIGN SIMULATION SOFTWARE ELEMENTS

Unfortunately, no single software can be recommended for all analysis types, levels of complexity, skill levels, and project types. Further, design simulation software advances are rolled out each month and year, so any comprehensive comparison of software functions and attributes is inherently out of date. Instead of attempting to list the best software for each situation, this section gives the reader a background and the right questions to ask when choosing software to help them make better decisions.

Running a simulation requires three pieces at a minimum: a user interface, a method of creating or receiving 3D geometry, and an engine.

A *graphical user interface* (GUI) is the look and feel of the design simulation software: the buttons, controls, inputs, outputs, and graphical displays. These allow the simulator to input and change parameters required for the software engine to perform its work. A good GUI will detect thermal zones and material properties from 3D software, and be able to locate grids of sensors within base 3D geometry. Automated GUIs contain default inputs to reduce the time required to set up a simulation, and allow the user to view and change the input parameters. Black box software, where inputs cannot be seen or changed, should be avoided.

Using characteristics of artificial intelligence, GUIs increasingly suggest design alternatives based on climates, typologies, and simulation results. These are no substitute for architectural skill, knowledge, and research, but can be helpful.

Three-dimensional modelers allow the creation of geometric forms with material assignments. While most sellers of design simulation software claim interoperability with a variety of 3D modeling programs, in practice, each one works best with one or two 3D modelers, omitting or misinterpreting geometry from other programs. Some software contains a native 3D modeler, forcing the simulator to learn a new program. For these reasons, the ability to test software in-house within a project context is extremely important.

While using the same 3D model for architectural layout, solar irradiation, daylighting, airflow, and energy modeling simulations would be ideal, models are often significantly modified or specifically built for each type of analysis. This is done to frame the question more specifically, to test options, and to exclude extraneous geometry and reduce run-time. With faster computers and cloud-based software this may become less of an issue. Green Building XML, commonly called gbXML, allows the translation of 3D geometry between software, plus any meta-data (such as thermal zones) associated with energy modeling. Most energy modeling and 3D modeling software can save to this format, though not all data always translates thoroughly.

11.1

Some software packages.

Graphical User Interface and Native Tools	3d Modeling Interoperability	Integrated Exports to Analysis Engines
Autodesk Vasari uses Ecotect Tools: - Insolation - Wind Analysis - Green Building Studio/ Revit - Energy Analysis (Automated Energy Modeling GUI) - Others	- Uses Revit 3d BIM modeler - Imports most 3d models	- DOE 2.2 (Energy Modeling Engine)
Autodesk Ecotect - Insolation - Rudimentary energy modeling - Rudimentary daylighting - Acoustical - Weather Tool (Climate Analysis) - Green Building Studio (Automated Energy Modeling GUI)	- Native 3d modeler - Imports 3d models	- Radiance (daylighting engine) - Daysim (daylight autonomy GUI) - DOE 2.2 (Energy Modeling Engine)
IES Virtual Environments Packages: - VE-Pro (Full engineering software) - VE-Gaia - VE-Toolkits (limited functionality) - VE-Ware (free)	- Imports 3d models	Proprietary engines (called Modules) for:: - Energy (based on ESP-r engine) - Solar - Light - HVAC - Climate - Airflow - Others
Diva for Rhino - Insolation	- Rhinocerous 3d modeler - Grasshopper 3d parametric modeler	- Radiance (daylighting engine) - Daysim (daylight autonomy GUI) - evalglare (glare analyses) - EnergyPlus single-zone simulations (energy modeling engine) - Others Freeware plugins for Rhino: - Ladybug (allows weather files as parametric inputs) - Galapagos (evolutionary solver) - Geco (Grasshopper/Ecotect inter face)
NREL OpenStudio: native Parametric Analysis Tool Contains libraries of: - building components - HVAC systems - glazing products - schedules. - others	plugin withinn SketchUp imports 3d models native modeler	- EnergyPlus (energy modeling engine) - Radiance (daylighting engine) - Glare analysis

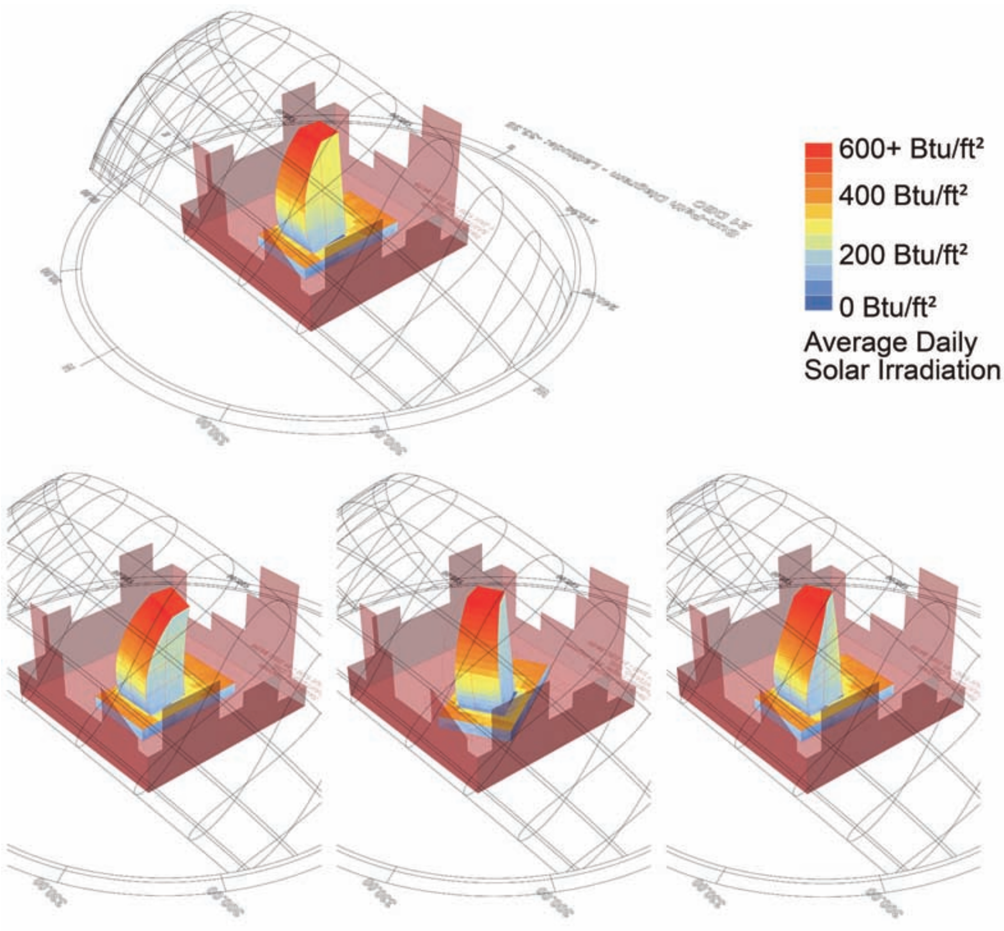
Engines contain complex formulas and tables that simulate the interaction of elements in the physical world. Each engine achieves a unique balance between computational abstraction and accuracy, computer run-time, and the level of detail required for inputs.

Plug-ins and *modules* are additive software elements that increase functionality. In many cases they are created by passionate individuals and offered for free or inexpensive download to solve a unique simulation problem. Free plug-ins are often released with few instructions and may contain some quirks.

SOFTWARE PACKAGES

The analysis types described in this book can be done, in most cases, by any number of software. The software described below shows some of the front-runners for architectural use. However, software is advancing rapidly enough that more software exists that can be compared against these to determine the best fit for price, ease of learning, available training, rigor, continual advancement, or interoperability with an individual's preferred 3D modeler.

- Autodesk, which bought Ecotect in 2008, has moved some of its functionality into Revit, a widely used BIM software. Vasari is used as a testing ground for new ideas that may eventually be incorporated into Revit. It includes a variety of design simulation analysis capabilities in each version, including an export to the Green Building Studio, which is an easy-to-use web-based GUI that runs DOE-2 energy analysis. Vasari currently incorporates a test version of architect-usable CFD software for exterior analyses.
- IES-VE comes in four levels of detail, from the free VE-Ware to the highly detailed VE Pro. The energy modeling engine is proprietary (though based on open-source ESP-r engine), as are a variety

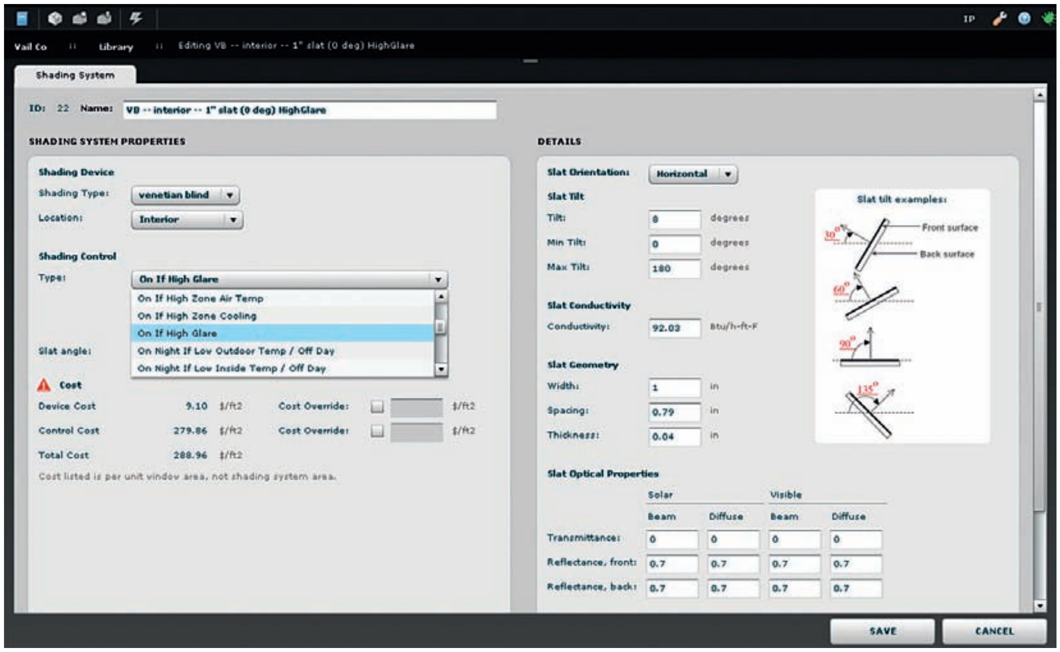


11.2

Software now allows real-time, interactive solar radiation studies. A simple mass can be created and distorted with solar radiation false colors immediately applied using the GenCumulativeSky algorithm. These studies were produced in about five minutes for a project in Santiago, Chile, using the Ladybug plug-in for Grasshopper. The west façade solar gain is shown as reduced from the "yellow" range to the "blue" range through a bend in the upper floors, a 30° rotation, or a twist at the upper floors. The Ladybug plug-in for Grashopper was created by Mostapha Sadeghipour Roudsari.

of modules that allow insolation, daylight, airflow, and a wide variety of other analysis types. It can use SketchUp as a base 3D modeler. IES-VE is rigorous enough to be used by professional energy analysts to evaluate mechanical designs and submit for energy code compliance, and it is the most costly of the software listed here.

- Diva for Rhino is the most complete of the many design simulation tools that operate within the Rhinoceros 3D environment and is relatively inexpensive. Diva interacts easily with Radiance and Daysim, as well as a native, annual Daylight Glare Probability measurement. The development team includes individuals engaged in building research, so it is likely to develop new simulation tools more quickly than other software. It can perform single-zone analysis using the EnergyPlus engine. One of the advantages of Rhino-based modeling is Grasshopper and other free tools that allow parametric, iterative modeling. For example, weather files can be used as geometric inputs using a module called Ladybug, and the GECO plug-in allows Ecotect simulation results to be used to create geometry.
- OpenStudio is a freeware from the National Renewable Energy labs that can produce whole building energy simulations (WBES) and daylighting analyses. It can run from within SketchUp, import geometry, or use a native modeler. It includes advanced tools to estimate energy performance, as well as for daylight and glare simulations.
- Sefaira is a newcomer to the design simulation field, although it is rapidly gaining market share and the development team is adding new features monthly based on user priorities. It interfaces easily with Simple SketchUp models and has the most graphic user interface available for a multi-zone energy modeling software, allowing early design options, including geometric options, to be quickly tested and compared. Sefaira has developed a proprietary thermal engine.



11.3

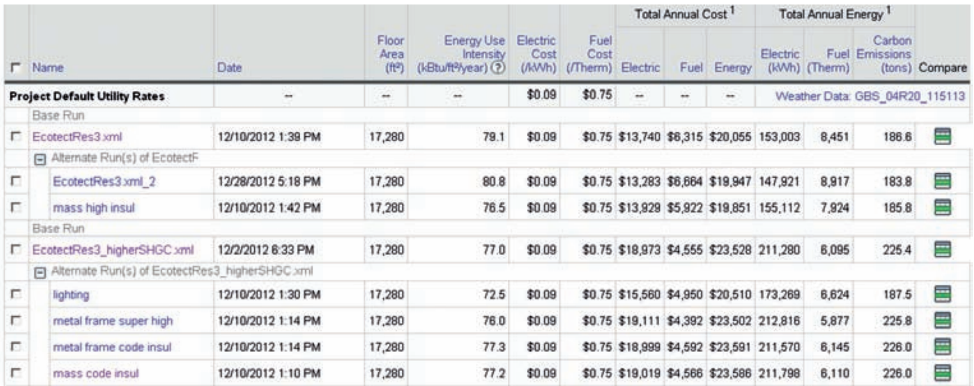
Good software provides good defaults, a library of options, and allows the user to customize materials and other parts of a simulation. This COMFEN screen allows the user to create a custom shading system that may match a product they want to test. Building controls, such as when to deploy the blinds, can also be assigned to each shading type.

Source: Courtesy of LBNL.

Some other packages that are useful, but are limited in scope or require extensive training:

- Passivhaus PHPP is an Excel-based software that predicts energy use and calculates compliance with Passivhaus energy use standards. The standards originated in Europe where tens of thousands of buildings have been Passivhaus certified. While not intuitive, it is very accurate and includes consideration of thermal bridging and more detailed air leakage calculations than other energy modeling software.
- Design Builder contains a full suite of tools, and runs the Energyplus engine for thermal calculations. It can also export to Radiance. It is rigorous enough to be used for compliance.
- eQuest is an older freeware GUI for the DOE-2 engine that is widely used by engineers and some architects. While it is more cumbersome than software targeted for architects, it is a full energy modeling program that can be used for quick, shoebox models, and can be a good exploration tool to understand the level of detail that full energy models use.
- COMFEN is a freeware from Lawrence Berkeley National Labs that performs shoebox modeling within a single zone. It is intended to compare fenestration, orientation, and shading options using the EnergyPlus engine. Though it is limited in scope, it is the most intuitive software currently available for early energy modeling, and it can easily teach the relative importance of various fenestration design moves.
- Climate Consultant is a freeware that graphically displays weather data, and does cursory analysis suggesting appropriate strategies for a given climate. It is very easy to use.

Of the more than 20 architecture firms interviewed for this book, all of the firms interviewed have used Autodesk's Ecotect product extensively, although most are transitioning to the next generation of design simulation software. Nearly all the firms use Radiance, exported from Ecotect's or Diva's interface. Many use the Grasshopper plug-in to Rhino for Design Simulation, and usually do not use Rhino extensively beyond Design Simulation. About a third of the firms use each of the following: Diva, Daysim, eQuest, and COMFEN. Sefaira is new enough that only a few firms in this survey use it although its uptake among architects over the last year has been noteworthy. Only a few firms used Vasari, SPOT, OpenStudio, and Climate Consultant. Only two firms felt comfortable doing in-house CFD analysis, though this is likely to increase as software companies such as IES, IDSL, and Autodesk are making CFD more automated and accessible.



Name	Date	Floor Area (ft²)	Energy Use Intensity (kBtu/ft²/year)	Electric Cost (/kWh)	Fuel Cost (/Therm)	Total Annual Cost[1] Electric	Total Annual Cost[1] Fuel	Total Annual Cost[1] Energy	Total Annual Energy[1] Electric (kWh)	Total Annual Energy[1] Fuel (Therm)	Carbon Emissions (tons)	Compare
Project Default Utility Rates	--	--	--	$0.09	$0.75	--	--	--	Weather Data: GBS_04R20_115113			
Base Run												
EcotectRes3.xml	12/10/2012 1:39 PM	17,280	79.1	$0.09	$0.75	$13,740	$6,315	$20,055	153,003	8,451	186.6	
Alternate Run(s) of EcotectF												
EcotectRes3.xml_2	12/28/2012 5:18 PM	17,280	80.8	$0.09	$0.75	$13,283	$6,664	$19,947	147,921	8,917	183.8	
mass high insul	12/10/2012 1:42 PM	17,280	76.5	$0.09	$0.75	$13,929	$5,922	$19,851	155,112	7,924	185.8	
Base Run												
EcotectRes3_higherSHGC.xml	12/2/2012 6:33 PM	17,280	77.0	$0.09	$0.75	$18,973	$4,555	$23,528	211,280	6,095	225.4	
Alternate Run(s) of EcotectRes3_higherSHGC.xml												
lighting	12/10/2012 1:30 PM	17,280	72.5	$0.09	$0.75	$15,560	$4,950	$20,510	173,269	6,624	187.5	
metal frame super high	12/10/2012 1:14 PM	17,280	76.0	$0.09	$0.75	$19,111	$4,392	$23,502	212,816	5,877	225.8	
metal frame code insul	12/10/2012 1:14 PM	17,280	77.3	$0.09	$0.75	$18,999	$4,592	$23,591	211,570	6,145	226.0	
mass code insul	12/10/2012 1:10 PM	17,280	77.2	$0.09	$0.75	$19,019	$4,566	$23,586	211,798	6,110	226.0	

11.4

The Green Building Studio is a web-based energy modeling user interface. Geometric models can be uploaded to estimate energy use and compare non-geometric trade-offs such as lighting energy use and envelope materials. GBS allows options to be run and then compared for overall energy use.

Source: Modified image of Autodesk GBS output.

CHOOSING SOFTWARE

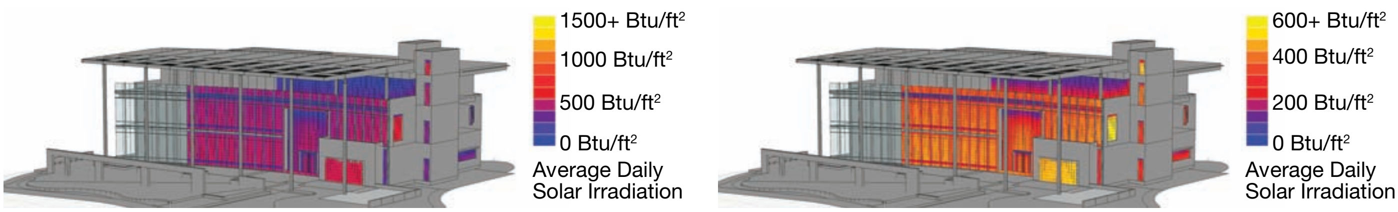
Some important things to consider when looking into a software:

1. The ability to test a full version within the workflow of a project is absolutely essential. Demonstrations run by software vendors and trainers make everything look simple.
2. The extent of training to reasonably run a simulation. Limited software that has been written to be intuitive, such as COMFEN and ClimateConsultant, requires little, if any, training. More complicated software requires training, which may not exist; if it does, it often costs more than the software when employee time is considered.
3. A software package should be intuitive and graphic enough in use and presentation that architects enjoy using it and can learn from it, unless only a specialist will be operating the system.
4. Interoperability with a firm's 3D modeling workflow needs to be tested first-hand.
5. A software should be able to export all results to spreadsheet format: this allows the design team to customize the data and graphical output format and calibrate the results with conditions beyond the software's scope.
6. Whether a software is web-based or computer-based. Web-based software lets results be shared among the project team members, with a variety of permission settings. Trained staff can upload geometry or edit certain data, other trusted team members can edit or run limited options, and the resulting information can be shared online with all team members.
7. Software that includes energy analysis capabilities should also contain libraries of default wall assemblies, glazing types, and HVAC system options appropriate to the design firms' typologies. The user should be able to see and change all defaults, as well as provide the ability to create or edit new materials, schedules, and other aspects. The software should only use weather data compiled from at least 15 years for annual analyses.
8. Parametric modeling is becoming more prevalent and useful to test many geometric options quickly in early design and adjust building geometry based on modeling results.

ACCURACY

The accuracy of a simulation depends on four major factors: the software engine, the inputs, the number of calibration runs, and the interpretation. Software has been tested for real-world accuracy to varying degrees, and is only tested for accuracy within a certain scope of use. Unusual simulations or those done by inexperienced modelers should always be compared against validated results or reviewed by experts before being used to inform building design. ASHRAE standard 140 can be used to compare the validity of energy modeling engines on a variety of common energy modeling tasks. However, the other three factors are often the source of inaccuracy.

Each software's methods of digitally abstracting reality can have a profound impact on the results, especially when unusual analyses are attempted. For instance, most energy modeling software cannot accurately simulate airflow in natural ventilation or in a double-skin façade. For daylighting, Radiance



11.5

Solar irradiation studies with false colors set to different thresholds. The image on the left looks deceptively well-shaded, while the image on the right is presented more correctly. False color settings need to be chosen carefully to understand and communicate the results of a simulation. For clarity, they often use the same upper and lower thresholds throughout a project presentation.

Source: Studies done using Autodesk's Ecotect Suite.

simulations have been rigorously compared to actual light levels and HDR photographs, and found to be photometrically accurate for typical daylighting scenarios. Case study 10.7 describes how Radiance daylighting analyses were used to calibrate the eQuest energy model's cruder daylighting results.

Default inputs provide the user with characteristics typical of a chosen typology, and based on building surveys or other research. Since most projects have some unique conditions, the simulator needs to understand all of the default inputs within an energy model so they can modify the necessary few on a given project. For example, the simulator may want to adjust a default lighting power density (LPD) from 1.0 $Watts/ft^2$ to .8 W/ft^2 based on anticipated code changes or the client's lighting goals. In many cases, a simulator needs to seek out additional resources for unique design simulation inputs. The research results in a deepened understanding of energy use and helps build a library that can be useful in the next project.

The first several runs of any simulation usually uncover flaws in the user's inputs. A standard office building with an EUI of 150 or 15 kBtu/sf/year tells the user that something is not correctly set up in the model. If the user cannot reconcile the results with their expected results, the user cannot rely on any results from the model.

For example, if a solar irradiation study in a sunny climate results in only 5 Btu/ft^2 on a west-facing window during the summer, the user needs to understand why this is the case. It could be that the north arrow was incorrectly placed, the wrong weather file was used, or a number of other issues.

With each subsequent run, input errors are eliminated and accuracy improves until the model is calibrated so that its behavior matches the user's expectation. Once calibrated, the user can change input variables, such as glazing type, geometry, or available thermal mass, to evaluate or compare design strategies that they are less familiar with. Professional energy analysts have noted in interviews that while some programs are highly accurate, a lower run-time can make up for accuracy by allowing more test cases to calibrate and refine the model.

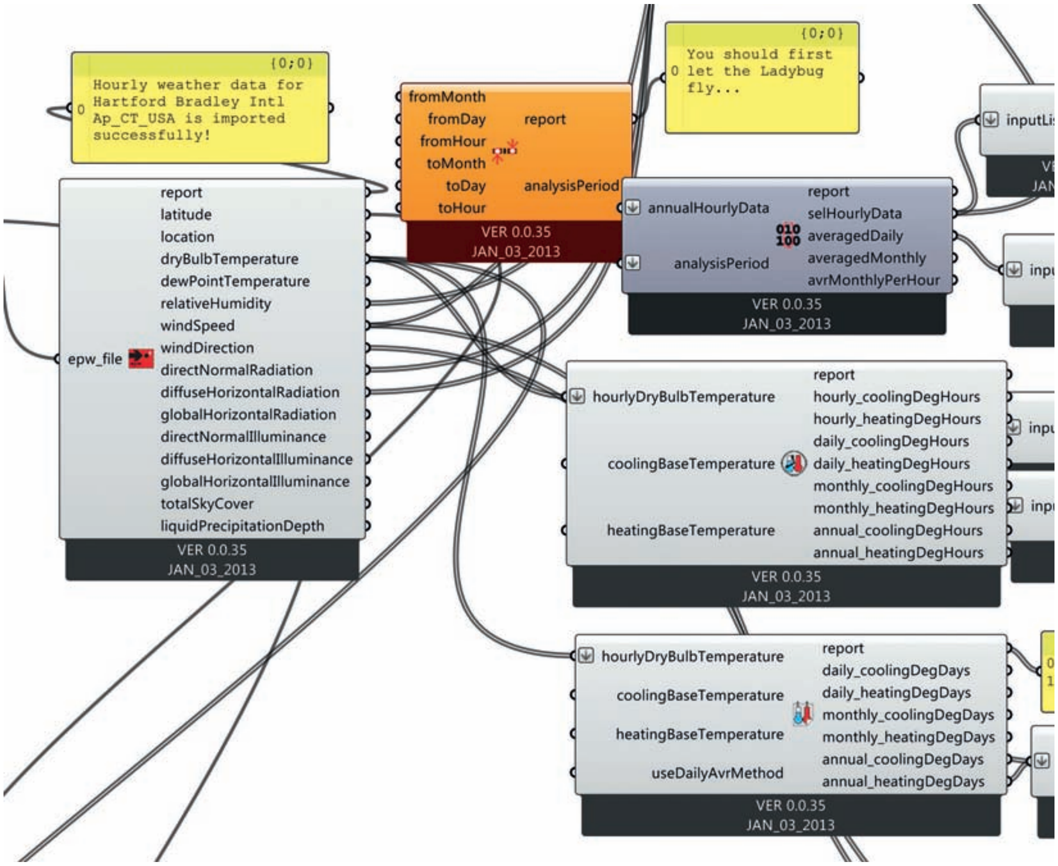
Interpretation is the last crucial step in accurate simulation. If the results have been calibrated through multiple iterations, then the final interpretation is simply a matter of summarizing the findings.

False colors are helpful to interpret and graphically convey spatial ideas of comfort, insolation, daylighting, or nearly any other metric. They can also be misleading. Presentations of results should use a single range of false colors for consistency and readability.

Most architects are better served by using comparative energy savings instead of predicted energy performance, removing some of the need to calibrate models to actual performance. For instance, if an energy model analysis estimates an EUI of 54 for Option 1 and an EUI of 50 for Option 2, the information can be presented as an 8% improvement. Since the two options share many input settings, and likely would maintain a difference of around 8% with many other combinations of settings, this is more accurate and defensible than quoting an EUI of 50. In early design, comparative results with a difference of less than 3% are considered as having similar performance, while differences or trends greater than 5% indicate that one option is very likely superior to another.

RESEARCH, STANDARDS, AND PRACTICE

This book represents the tip of the iceberg for design simulation. Individuals new to the field cannot possibly imagine the level of effort encoded within good software. For example, individuals and



11.6

Grasshopper parametric modeling tool showing weather inputs and variables, via the Ladybug plug-in.

institutions spend years researching and debating the best digital representation of the light distribution within a partly cloudy sky. We run simulations that rely on the rigor of this sky model, which has been vetted through countless studies, papers, technological advancements, and discussions.

Researchers study phenomena in buildings to find methods of characterizing interactions in the physical world. They invent new technology, new ways of using technology, and more accurate methods of predicting results. When enough evidence exists, standards bodies integrate research into their codes, standards, and other publications. They abstract the researcher's findings with enough granularity for professionals to understand and use.

Most end users, even energy modeling specialists, are often not aware of each abstraction that goes into the software or the latest research that may critique the accuracy of the abstraction. Instead, they become proficient at using the tools available to provide timely feedback to a design team, using research, experience, and standards and to improve their simulations' accuracy. They also may be part of user groups such as the International Building Performance Society (IBSPA) or software-specific user groups to achieve increasingly accurate results.

While engineers, researchers, and others work within a limited scope, architects deal with every potential problem and opportunity in building design. For this reason, architects are often casual users of design simulation software. As casual users, architects need to be able to investigate problems in concept-level detail within their workflow.

While architects who engage in modeling are interested in rigor, their firms often do not invest their time so they can spend hours a day on user groups to improve accuracy by a fraction of a percent. Although many of the large firms I spoke with have researchers as part of their practice, these individuals spend a majority of their time gathering and applying research to specific architectural projects.

Architects who connect with researchers can have a symbiotic relationship to deepen an architect's knowledge, improve sustainable design excellence, and help the researchers understand issues among practitioners,

The context of any researched information is important to understand. For instance, the *U.S. Department of Energy Commercial Reference Building Models of the National Building Stock by* the National Renewable Energy Laboratory contains tables on number of occupants by building type, outside air requirements, and more. The numbers in the above document were taken from the CBECS survey, so they apply to around 5,200 buildings in all climate zones in the USA. The inputs were used to create 16 prototype buildings for running standard energy simulations, so they are reasonable assumptions to include in a typical building. However, for project teams targeting low-energy goals and attempting to simulate unusual systems, much more research needs to be done in order to validate inputs into a model.

In many cases, the additional research is done by mechanical designers and professional energy analysts, though architects are not discouraged from research. For instance, plug loads are increasingly becoming important in low-energy design. Instead of relying on tables, the West Berkeley Library team measured actual plug loads at the former library for their simulations.

CONCLUSION

Design simulation works when the project team follows the scientific process—generating and framing questions, testing design solutions, and implementing the better solutions into the project. There is no single software appropriate for answering each question with the right level of detail, ease of use, and integration with a wide variety of 3D models. Instead, most firms invest in a few pieces of software and training appropriate for their most common types of analysis and that works with their preferred 3D modeler. Each case study in this book lists software used, though most complete package software can do a wide range of analyses.

Since software sophistication continues to mature quickly, firms that do in-house simulation can expect that the range of simulations possible and ease of use will continually improve.

12

Design Simulation in Practice

In theory, theory and practice are the same. In practice, they are not.

—Albert Einstein

While the American Institute of Architects was founded to "promote the scientific and practical perfection of its members," I have been disheartened through my career about the lack of interest in science among architects, and of research and development among architecture firms. As architects have ceded energy performance and research to engineers, we have regressed in our understanding of how building design affects energy use and comfort.

The recent trend of including building energy performance and simulation within the education and practice of architects is encouraging. It needs to accelerate so our profession can do our part to mitigate the worst effects of climate change.

An overwhelming number of resources exist to guide low-energy design: blog posts, online and journal-published papers, free and pay-for-use software, online tools, rules of thumb, very technical manuals, cursory software overviews, examples in magazines, and many others. Navigating the multitude of resources to provide relevant guidance for sustainable design challenges every design firm. Many firms have settled on a canon of books, resources, and one or two pieces of software assist in making informed decisions.

In general, architects will not engage design simulation unless it is the right combination of intuitive and useful. While the usefulness has been apparent for years, no general training for architects exists and design simulation software historically has not been intuitive. Today's software significantly eases the path for practicing architects to use the software within the design process. University training for students is becoming more commonplace, and training for professionals is expanding, though it is usually provided through a software company and is limited to one specific software.

Instead of following prescriptive codes, which necessarily restrict design, simulation offers freedom to achieve a given performance. Incorporating design simulation today allows firms to anticipate the likelihood of energy codes transitioning to a performance-based approach.

The previous chapters have discussed how the tools can be used; this chapter goes through how their use is integrated into practice: who performs simulations and how design teams engage simulation as a normal part of the design process.

THE DESIGN SIMULATION PROCESS

The modeling methods described in this book have become part of many firms' design process because they provide a good balance between speed, accuracy, and usefulness. Most single-aspect analyses done as part of the case studies in this book can be done in 4–16 hours of project time, though the teams have studied options beyond those shown. A wide variety of options and sequential studies can increase this amount of time, of course, as can increasing the level of detail.

Nearly every architectural firm interviewed for this book had faced challenges connecting their design simulation program with each project team at the optimum time. Project schedules are tight, the right people are not available when needed, and some individuals are leery of an energy-based critique of their designs. Most projects include periods when design simulation can effectively assist in decision-making, referred to as the design simulation "window." At other times, decisions have already been made and production is more important.

The success stories happen when project budgets are written to allow the Design Simulation Group (DSG) to interact with the project team, when enough individuals are trained so that each project has access to a DSG member, and when project teams value the contributions of the DSG.

FIRM PROFILES

For this book, the author interviewed members of over 20 architecture firms that have in-house design simulation programs, as well as engineers, researchers, and others who are engaged in improving building performance. Most of the firms interviewed have over 30 employees, giving them the ability to hire or develop an individual with some experience in design simulation. However, this specialization is not necessary to use some of the free, easy-to-use tools described in Chapter 11, such as COMFEN and Climate Consultant.

Of the 20 architectural firms interviewed:

- Three firms have in-house mechanical engineers.
- Four architecture firms have in-house energy modelers but no in-house mechanical engineers.
- All the firms used Autodesk's Ecotect, though most were transitioning to other software.
- Nearly all the firms used Radiance, often exporting from Ecotect.
- Half the firms use Rhino and Grasshopper to assist with design simulation.
- Most of the architecture firms had 2–3% of the design staff as full-time sustainability or design simulation specialists.
- Firms generally considered design simulation an integral part of their process instead of an additional service.

Most firms voiced frustration with their lack of interaction with mechanical engineers. In most cases, clients do not allow their hiring until most of the geometric decisions have been made. In other cases, the engineers do not have the fee or interest in performing quick, iterative studies, running models without detailed inputs, or looking at non-standard options. The goal of in-house design simulation is not to diminish the role of mechanical engineers, but to make sure that someone with analysis capabilities is embedded in every project during the early design phases.

All three architectural firms with in-house mechanical engineers also have a group that specializes in early analysis and acts as translators between architects and engineers. The individuals who make up this group include architects who have learned simulation, daylighting specialists, and others who are nimble enough to deal with the unknowns of early design.

Four of the architect-only firms employed at least one individual to do Whole Building Energy Simulation (WBES) in-house. This individual does not design mechanical systems, but can set up and run the rigorous shoebox and compliance energy models that later design stages and LEED submittals require. Since the individual is integrated into the design team, the inputs are coordinated with the latest options and models can be run as often as necessary. This has been especially effective in firms where a single typology dominates an area of practice, where clients are interested in energy use and life cycle paybacks, and where post-occupancy data is available to calibrate the design simulations.

Beyond those four, some other firms had an individual with eQuest experience who could perform quick, specific shoebox energy models on projects even in the competition phase.

A DESIGN SIMULATION GROUP

The individual or group doing early design simulations can be referred to as the Design Simulation Group (DSG), though its members likely have other roles within the firm. It has been surprising to learn how the DSGs in many firms often are very much an embodiment of one or two individuals' skills and motivations, so firms are often very good at one type of simulation but have not explored others covered in this book.

The members of the DSG generally include architects who understand building science, "sustainability team" members who may operate software as well as leading eco-charettes and writing White Papers, and dedicated specialists in daylighting, energy modeling, or parametric software. Ideally they are embedded in each team, but in practice this is challenging.

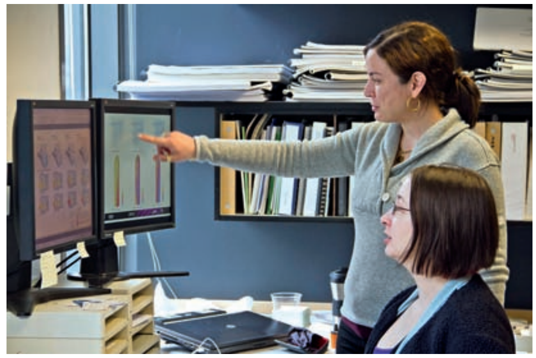
The DSG will occasionally need to verify that early design modeling is indicative of later performance. This can be accomplished by doing a more detailed study at design completion, a post-occupancy study, or comparing the early design EUI with a professional energy modeler's results, for example.

CALLISON'S STORY

Callison's design simulation story begins with Ecotect, like many other firms. Symphysis was hired to train 12 staff in 2008, and shortly thereafter we formed an in-house Ecotect Users Group. We met at bi-weekly lunches to discuss how we had used the software to run analysis on our projects.

We quickly realized weather data outputs were graphically compelling, easy to create, and powerful for understanding and formulating a climate response. After the first climate analyses were created for projects in Vail, Colorado, and Delhi, India, other project teams took notice; within six months of the Ecotect training, the Callison Board required every project to engage the newly formed climate team to provide a three-page climate analysis. The template continues to evolve as we explore new and more effective ways of understanding climates. As of 2013, over 60 climates worldwide have been analyzed. We continue to train several staff each year in climate analysis—both the technical manipulation of software and the interpretation of the results.

Callison's in-house program continued to evolve as our understanding grew; we added Green Building Studio to our toolkit, as well as Radiance daylighting software with help from the University of Washington Integrated Design Lab. Our simulations' graphic results allowed us to more easily interpret and convey quantitative information to a project team, our clients, and along a project timeline.



12.1

Two members of Callison's energy modeling team.

By 2010, with more than 10 projects that had substantially used design simulation to inform decisions, we felt ready to roll it out. Callison was exploring ways of meeting our internal sustainability goals and the recently signed AIA 2030 Commitment. The Board asked the author to create a wider design simulation program in early 2010. I put together a 32-hour course and trained 12 staff in Seattle, 3 each in Dallas and Los Angeles, and 6 in Shanghai to initiate the effort.

The trained team in Seattle met monthly to share techniques and explore new methods and software. We have continuously tested other software through the writing of this book, but each one was not ready to compete with the ease of use, graphic nature, or scope of the Ecotect Suite. A revamped program, however, will incorporate the next generation of software.

Callison's design simulation program was featured at Greenbuild 2011, and provides the backbone for this book. Many other firms have created their own paths documented here as well; hopefully our combined efforts will inspire all firms to begin, expand, or re-invigorate design simulation programs.

DESIGN SIMULATION AT YOUR FIRM

The Design Simulation Group at your firm will be a bridge between architects and engineers. The individuals within the DSG should have the ability to convey complex information quickly and graphically, an interest in energy and systems, and good rapport with design teams. They need a general understanding of the design process, programming, massing, and building typologies, and should be flexible enough to work with architectural designs in their early stages among constant change and many unknowns. In general, employees who understand building science and are at ease with 3D software can be trained to do design simulation.

Establishing a design simulation program requires at least one individual with the passion, experience, and inquisitive nature to lead the effort and provide training and technical support to others who may use design simulation software. Most firms tiptoe into design simulation with daylighting and shading analysis, since they are easier to understand.

In order to ensure reasonable accuracy, an individual with a building science or energy modeling background, or one with years of experience in design and construction, needs to oversee the set-up and results of each model. Models are complex; making decisions based on Design Simulations requires a level of confidence in the abilities of those running simulations to understand and interpret the results, equal to the complexity of the model. Jason McLennan, CEO of the Cascadia Green Building Council, led a building science team known as Elements at BNIM Architects. As he puts it, designers used techniques "sometimes powerfully, sometimes in ways that made me cringe."

Support from technology specialists is essential to test and implement most new software, especially freeware and plug-ins, since they tend to be quirky. For example, Radiance software needs to be installed with no spaces or unusual characters in the path name.

Large firms that push the boundaries often will have specialists to customize software, write scripts, and explore the possibilities of iterative, parametric modeling. The interaction between design architects and these specialists can produce amazing results. Firms that use Grasshopper have an especially potent tool to generate forms based on climate and site issues as the case studies show.

RESOURCES

Many of the complaints about design simulation are really complaints about the non-linear process of early design instead of about the tools themselves. When design teams are informed, they make better decisions, even if the best option isn't always chosen.

Few engineering or specialist firms offer simulations in 8- or 24-hour contracts. For firms that do not have in-house expertise or would like more expert help, many communities have simulation resources. For the Bullitt Center (anticipating a Living Building Designation), architecture firm Miller Hull collaborated with the non-profit Integrated Design Lab in Seattle for daylighting studies. The IDL also collaborated on the Austin Central Library with Lake Flato Architects (Case Study 8.3). Resources are listed in each chapter; those that are common to all chapters are listed below:

- The ASHRAE *Handbook of Fundamentals* (2013) is an essential reference for standard and non-standard inputs for automated energy models, as well as describing general processes that underlie energy modeling efforts.
- The New Buildings Institute website has resources for Lighting and Daylighting and HVAC systems.
- Wikipedia is a great first resource for understanding basic elements. More rigorous information is always essential to corroborate due to Wikipedia's open format.
- The International Building Performance Simulation Association is a motivated group of specialists that publishes papers and holds conferences to validate and share modeling and analysis methods.
- Many communities have access to resources such as daylighting labs, comfort labs, and universities where research is done and techniques are taught. Case Study 8.6 highlights the collaboration between the University of Washington and LMN Architects.
- Blogs and user groups can be very helpful as well; many are quoted or listed within the chapters.
- Conferences such as Diva Day or Autodesk University gather practitioners to share techniques.

CONCLUSION

In order to achieve the 2030 Challenge goals necessary to avert the worst effects of climate change, architects need to re-learn how to design for building performance, integrating it into our profession. This book attempts to coalesce many of the disparate components of low-energy design simulation within a framework that allows casual and high-powered users to better their ability to analyze their projects and make more informed, sustainable decisions.

Beyond simply validating our designs, architects need to learn how to play within design to create spaces that are exceptional in performance and aesthetics. The act of designing alongside the simulation process is the best guide to learning how to design more sustainable spaces and buildings.

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