

Building Energy Modeling with OpenStudio

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A Practical Guide for Students and
Professionals

 Springer

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The authors dedicate this book to their families.

*For Larry Brackney:
Raina and Nola*

*For Kyle Benne:
Ashley and Desmond*

*For Daniel Macumber:
Kristin, Tori, Lizzy, and Natalie*

*For Andrew Parker:
Lisa and Penny*

Foreword

The energy, environmental, and societal challenges of the twenty-first century are here; they are crystal clear; and they are daunting. Our responses to those challenges are less clear, but one component at least is obvious—we need a better building stock, one that uses less energy, provides greater comfort and security, and houses and supports the economic activity of a rapidly growing and urbanizing population.

One of the most powerful tools in our collective belts is building energy modeling (BEM), physics-based software simulation of building energy use given a description of the physical building, its use patterns, and prevailing weather conditions. BEM is a *sine qua non* tool for designing and operating buildings to the levels of energy efficiency that our future and present require. According to the AIA 2030 Commitment report, buildings designed using BEM use 20% less energy than those designed without it. BEM is also instrumental in developing and updating the codes, standards, certificates, and financial incentive infrastructure that supports energy efficiency in all building projects, including those that don't directly use BEM.

Today, every man-made artifact of any significance—from razors to race cars, potato chips to computer chips, cardboard boxes to big box stores—is prototyped virtually before being built and tested physically. Would you get on an airplane for which only two prototypes were built and whose design and systems weren't tested under a range of conditions over millions of hours of computer simulation? I hope not. Would you shave with a razor that hasn't undergone tens of thousands of hours of computer simulation? You probably would, but in actuality you do not—the margins on razors are sufficiently small that both razors and the machines that produce them have to be optimized to a degree that only computer simulation can manage. Why should razors be modeled and buildings not? Buildings provide a greater range of more important functions, and over much longer service lifetimes. The economics of building physical prototyping are more prohibitive; an owner will not pay to build and test multiple prototypes before settling on the final version. And most buildings—at least most commercial buildings—are essentially

one-offs, sufficiently different from all other buildings in terms of local context project specifics so as to make high-level lessons transferrable but not full designs.

Yet, curiously and unfortunately, most buildings are still designed without the use of BEM. The same AIA 2030 Commitment report shows that only 43% of the new commercial floor space reported in 2017 used BEM during the design process. And that number is likely inflated by the fact that the Commitment is voluntary and that efficiency focused firms are over-represented in it. Anecdotal evidence suggests the real number is closer to 20%. That will not do at all.

The mission of the US Department of Energy's (DOE) Building Technologies Office (BTO) is to envision and enable a more energy-efficient building stock. BTO has identified increasing the use of BEM in building design as a high-priority high-impact vector in achieving its larger energy-savings mission. BTO's BEM program centers on the development of a state-of-the-art open-source BEM platform, which consists of the EnergyPlus BEM engine; the OpenStudio software development kit (SDK), which facilitates application development, workflow automation, and large-scale analysis; and the star of this book, the graphical OpenStudio Application.

The OpenStudio project has been a driving force in the evolution of BTO's BEM program. OpenStudio was BTO's first truly open-source software project, a strategic direction that has influenced BTO's entire BEM portfolio. Open-source is not an altruistic emergent enterprise. Successful open-source projects are funded, centrally managed, and resemble proprietary software projects in many structural and operational ways. Source control. Code reviews. Regression testing. Bug reporting and fixing. Pre-feature documentation. Post-feature documentation. The full Monty. Open-source is different in that it is transparent—anyone can inspect the algorithms and see how they are implemented under the hood. Transparency is crucial for BEM, which has many financial and regulatory use cases. And it is different in that it gives others the freedom to take the software and build upon it without paying a fee, signing a non-disclosure agreement, or even notifying the original authors. The open-source license used by OpenStudio allows derivative works to be proprietary and commercial. For OpenStudio and BTO, open-source has been an accelerant for industry and user adoption. EnergyPlus was re-released under an open-source license in 2012. Between 2012 and 2016, EnergyPlus downloads increased from about ten thousand per version to over forty thousand and the number of third-party applications using EnergyPlus grew from three to well over a dozen. The larger software industry has learned to live with and profit from open-source projects, the BEM industry is doing the same.

OpenStudio brought other modern software paradigms to BTO's BEM program, and, in some cases, to the BEM industry as a whole. A library structure with a rich application programming interface (API) created the classic three-layer engine-middleware-application architecture found in many computer systems—think of a smartphone's hardware-Android-apps setup—that fosters innovation and adoption. Online libraries that can complement centrally curated content with “crowd-sourced” content. Scripting, which OpenStudio calls Measures, improves

BEM workflow productivity, adds a layer of transparency to common BEM tasks, and transfers BEM process expertise. Scripting acts as a building block for large-scale BEM analyses. Software packages can run on commodity cloud services and allow anyone with a credit card to set up and run said analyses. Web technologies for interface development. Textbooks as BEM teaching tools!

This textbook is visually heavy on the OpenStudio Application. As every kid learns at a young age, books are much better with pictures! But like any good textbook, this one stresses universal concepts. The pictures simply hold your hand as you learn these concepts the way learning is done best, by doing. If you are a beginning student, you will learn how to use most of the basic features of OpenStudio. You will also learn the basic components, structures, and processes of BEM; weather data; thermostat set-points; constructions; schedules; thermal zoning; simple HVAC systems; output reports; and diagnostic variables. These constructs are ubiquitous and work in essentially the same way in every BEM tool. If you are a more advanced student, you will see Measures and learn how to work with the OpenStudio Parametric Analysis Tool. You will also learn how to think about model transformations algorithmically, how to organize design variants, when to use large-scale analysis and optimization and how to constrain it so that produces meaningful results, and how to reuse not only concepts but actual work from one project to the next. You will learn about OpenStudio, but you will gain a basic understanding of BEM and its processes that you can take with you to any other tool. You will get a fish *and* learn how to fish.

I hope this book helps you find a passion for BEM and that, OpenStudio or not, you decide to pursue it more seriously and maybe even professionally. Thank you for choosing to learn about this fascinating and important field.

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February, 2018

Amir Roth

Preface

This book is intended to provide advanced undergraduate and graduate students with an introduction to the topic of building energy modeling, simulation, analysis, and optimization. It is assumed that the reader has a basic understanding of fluid mechanics, thermodynamics, and heat transfer and is prepared to apply those fundamentals to more complex systems. The authors believe that this book will also be of value to energy efficiency professionals who are actively engaged in improving the built environment.

A number of software tools exist to model and simulate individual buildings, and many of the concepts discussed in this text are applicable to them. That said, the authors have structured this book around an open-source platform called OpenStudio and its underlying EnergyPlus simulation engine. OpenStudio is intended to facilitate the creation of many tools that make use of energy simulation to enable decision-making by diverse stakeholders at each stage of a building's lifecycle. The platform contains a number of attributes unique to energy modeling including an object-oriented data model, extensible scripting, and an analytical framework that scales from individual buildings up to portfolios. The reader will experience these and other features of OpenStudio and EnergyPlus throughout the book using a pair of example applications built with the platform.

Instructors should find the material organized in a sequence that slowly builds in complexity, enabling students to gain fundamental knowledge while applying new skills as they progress. To that end, each chapter concludes with one or more "checkpoint" exercises, so-named because they generally result in a usable model that is built upon in a subsequent exercise. The authors consider the checkpoint exercises as integral to the book's content, and we strongly urge students to work through them in their entirety.

While we believe the exercises are organized in the most appropriate order, instructors can elect to have students work through checkpoints one and three before proceeding to checkpoints two, four, and onwards without impacting prerequisites for subsequent chapters. It is really up to the instructor's preference as to whether they wish to maintain student focus on rudiments or begin mixing in sophisticated applications that expand on those fundamentals more rapidly.

The final third of the book contains advanced material that may be more appropriate for graduate students or professionals. The authors believe the material in these chapters is well suited to prepare graduate students for a variety of research tasks,¹ however we have attempted to balance that with practical applications that are approachable and will have resonance with current (or soon-to-be) professionals. Again, we have attempted to organize material in the text to provide the instructor with the greatest flexibility in adapting it to the needs of their students.

Whether you are a student, instructor, or practicing energy efficiency professional, it is our sincere hope that this book will be useful to you in learning about how the energy performance of the built environment is modeled and analyzed. Perhaps more importantly, it is our hope that you will use what you learn to make a real difference in how buildings impact the environment that we all share.

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¹The authors and their colleagues at NREL regularly use OpenStudio on a large number of research projects for the US Department of Energy and other clients.

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Abbreviations and Acronyms

AEDG	Advanced Energy Design Guide
AIA	American Institute of Architects
AMI	Amazon Machine Image
AMY	Actual Meteorological Year
ANL	Argonne National Laboratory
API	Application Program Interface
ASHRAE	American Society of Heating, Refrigeration, and Air-Conditioning Engineers
AWS	Amazon Web Service
BCL	Building Component Library
BEM	Building Energy Modeling
BLAST	Building Loads Analysis and System Thermodynamics Program
CAD	Computer Aided Design
CB ECS	Commercial Building Energy Consumption Survey
CDD	Cooling Degree Day
CEC	California Energy Commission
CEUS	California End-Use Survey
CLI	Command Line Interface
COP	Coefficient of Performance
CPUC	California Public Utility Commission
CVRMSE	Coefficient of Variation of Root Mean Squared Error
CW	Cold Water
DCV	Demand-Controlled Ventilation
DOAS	Dedicated Outdoor Air System
DOD	Department of Defense (United States)
DOE	Department of Energy (United States)
DOE	Design of Experiments
DX	Direct Expansion
EC-2	Elastic Cloud Computing
EE	Energy Efficiency

EMS	Energy Management System
EPW	EnergyPlus Weather (File)
ERV	Energy Recovery Ventilation
EUI	Energy Use Intensity
HID	High-Intensity Discharge
HW	Hot Water
IDE	Integrated Development Environment
IDF	Input Data File
gbXML	Green Building Extensible Markup Language
GLHEPro	Ground Loop Heat Exchanger design tool Pro
GSHP	Ground Source Heat Pump
GUI	Graphical User Interface
HDD	Heating Degree Day
HTML	Hypertext Markup Language
HUD	Department of Housing and Urban Development (United States)
HVAC	Heating, Ventilation, and Air-Conditioning
IES	Illuminating Engineering Society
JSON	JavaScript Object Notation
LBNL	Lawrence Berkeley National Laboratory
LEED™	Leadership in Energy and Environmental Design
LHS	Latin Hypercube Sampling
LPD	Lighting Power Density
NBS	National Bureau of Standards (United States)
NBSLD	National Bureau of Standards Load Determination program
NIST	National Institute of Standards and Technology (United States)
NMBE	Net Mean Bias Error
NRCan	Natural Resources Canada
NREL	National Renewable Energy Laboratory
NSGA2	Non-dominated Sorting Genetic Algorithm 2
OA	Outdoor Air
ORNL	Oak Ridge National Laboratory
OS	OpenStudio
OSA	OpenStudio Analysis (JSON File)
OSM	OpenStudio Model (File)
OSW	OpenStudio Workflow (JSON File)
PAT	Parametric Analysis Tool
PLR	Part Load Ratio
PNNL	Pacific Northwest National Laboratory
PSO	Particle Swarm Optimization
PTAC	Packaged Terminal Air Conditioning
RECS	Residential Energy Consumption Survey
RGENOUD	R-GENetic Optimization Using Derivatives
RTU	Rooftop Unit
SAT	Supply Air Temperature
SDK	Software Development Kit

SPEA2	Strength Pareto Evolutionary Algorithm 2
TMY	Typical Meteorological Year
UID	Unique Identifier
URL	Uniform Resource Locator
VAV	Variable Air Volume
WWR	Window-to-Wall Ratio
XML	Extensible Markup Language

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