Building Performance Simulation: What's in the Black Box?

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Bentley Systems, Inc.
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ASHRAE Iowa Chapter

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Building Performance Simulation: What's in the Black Box?
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Building Performance Simulation: What's in the Black Box

By Drury B. Crawley

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General CE hours

LEED GREEN ASSOCIATE
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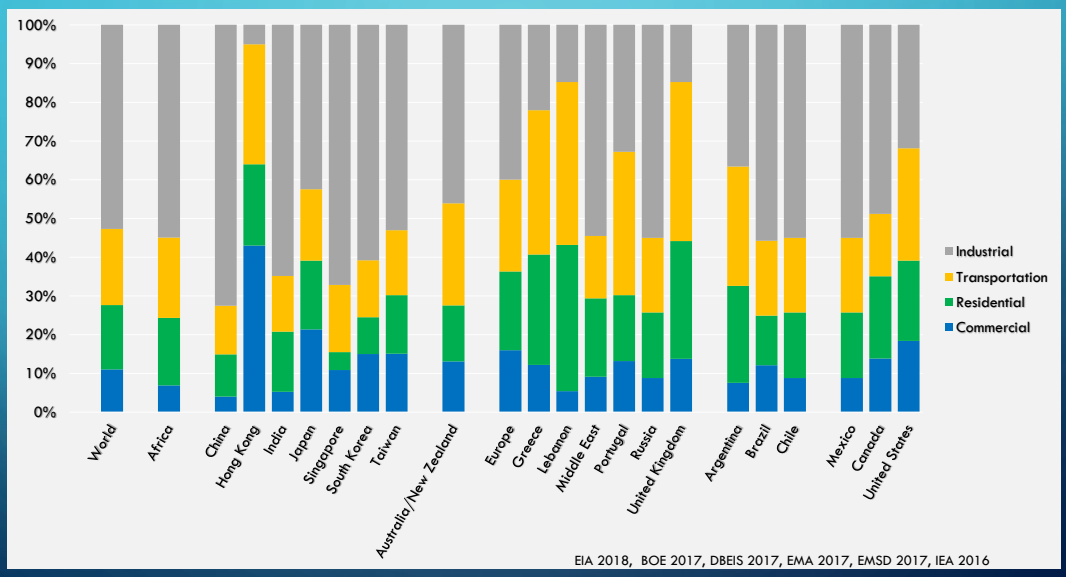
BUILDINGS ENERGY USE WORLDWIDE



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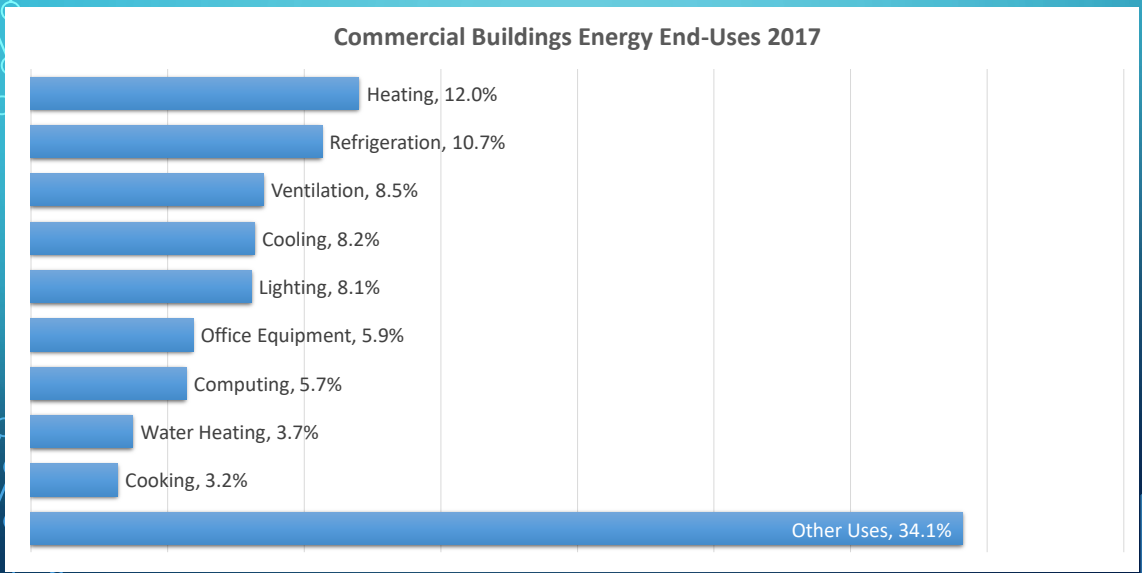
U.S. BUILDINGS ENERGY USE



US Energy Information Administration. 2018. *Annual Energy Outlook 2018* EIA-0383 (2018) (2017 data)

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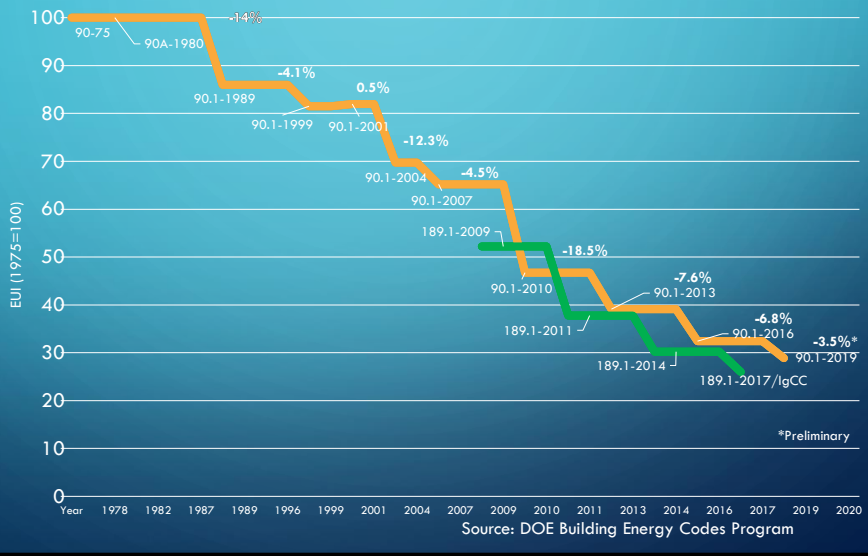
INCREASED STRINGENCY IN ENERGY EFFICIENCY AND GREEN STANDARDS



Source: DOE Building Energy Codes Program

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MODELING AND SIMULATION

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MODELING AND SIMULATION

- ***Model***: a **schematic description of a system,** theory, or phenomenon that accounts for its known or inferred properties and **may be used for further study of its characteristics**: a model of generative grammar; a model of an atom; an economic model. American Heritage Dictionary (2008).

- ***Simulation***: a mathematical exercise in which a **model of a system is established,** then the model's **variables are altered to determine the effects on other variables.** Scott (2003).

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WHAT IS BUILDING PERFORMANCE SIMULATION?

Software which emulates the ***dynamic interaction*** of heat, light, mass (air and moisture) and sound ***within the building*** to predict its ***energy and environmental performance*** as it is exposed to climate, occupants, conditioning systems, and noise sources

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BUILDING PERFORMANCE SIMULATION

- Still more art than science
- Major Issues:
  - Building data maintenance/storage throughout building life-cycle
  - Training…must train users in simulation methods not tools!
  - Tools must enable and encourage new technologies--too many technologies/systems that various tools cannot simulate
- Getting data from existing building information models (yes, BIM) is still a challenge.
- Green/sustainable design and policy are driving simulation more than energy costs (LEED, BREEAM, EPBD, Title 24, CalGreen, ASHRAE 90.1/IECC, 189.1/IGCC)

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BUILDING PERFORMANCE SIMULATION TRENDS

- New tools/capabilities in established tools
  - Interoperability—buildingSMART IFC, XML, BIM Standards
  - Visualization/VR/AR
  - Integration—thermal, CFD, electrical, IEQ, visual
  - Embodied energy, LCI/LCA, toxicity of built environment
  - Emissions
- More tools, not fewer, customized to user needs
- Users continue to want more capabilities but with less effort
- WARNING! Do you know what your defaults are?

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TYPES OF PROGRAMS AVAILABLE

- Simpler programs for overall energy consumption assessment, peak temperature prediction, heating/cooling loads calculations
- More complex programs for (sub)hourly simulation of heat, light and air movement
- Specialist packages, for lighting, computational fluid dynamics (CFD), acoustics, two- and three-dimensional conduction calculations
- Integrated design and analysis systems combining several

Building Practitioners

Experts

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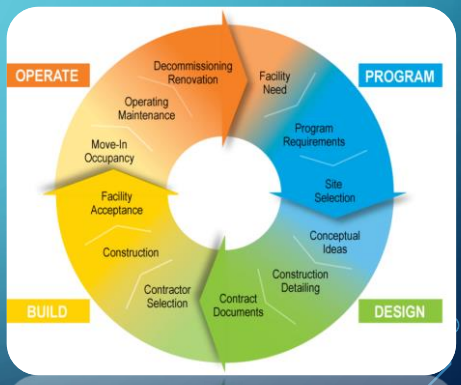
WHY USE BUILDING SIMULATION?

- Inform energy decisions from earliest phases of design through construction and into operation
- Focus energy-use reduction efforts where they will be most effective
- Evaluate alternatives through programming, design, construction, operation—retrofit, too
- Assess predicted performance against established benchmarks or project goals
- Cheaper to do simulations than constructing and paying for the wrong building!



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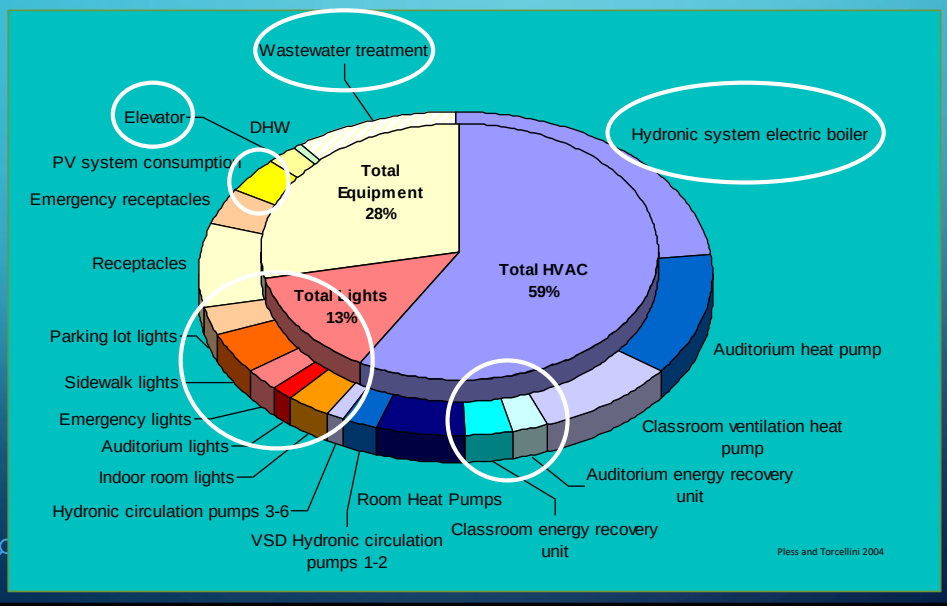
END-USE ENERGY: THE MORE DETAIL THE BETTER!



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SIMULATION VS. OPERATING ENERGY

- Simulation is a critical tool to support decision-making for building design and operation
- BUT, compared to simulations, real buildings often:
  - Use more energy
  - Produce less power
  - Have worse controls
  - Have more occupant complaints
  - GIGO
  - Not enough information!

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"Every building is a forecast. Every forecast is wrong."

Stewart Brand
How Buildings Learn, What Happens after they're Built

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WHAT'S INSIDE THAT BLACK BOX SIMULATION PROGRAM?

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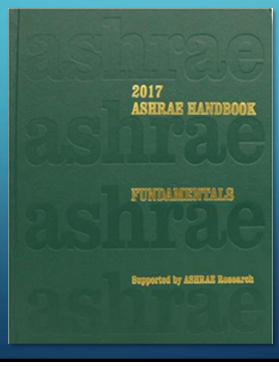
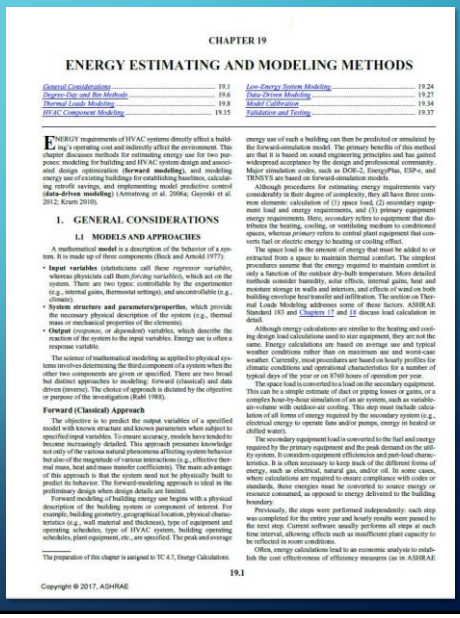
ASHRAE 2017 FUNDAMENTALS

Chapter 19

Energy Estimating and Modeling Methods





CHAPTER 19

ENERGY ESTIMATING AND MODELING METHODS

General Considerations 19.1
Degree-Day and Bin Methods 19.6
Thermal Loads Modeling 19.8
HVAC Component Modeling 19.15
Low-Energy System Modeling 19.24
Data-Driven Modeling 19.27
Model Calibration 19.34
Validation and Testing 19.37

ENERGY requirements of HVAC systems directly affect a building's operating cost and indirectly affect the environment. This chapter discusses methods for estimating energy use for two purposes: modeling for building and HVAC system design and associated design optimization (**forward modeling**), and modeling energy use of existing buildings for establishing baselines, calculating retrofit savings, and implementing model predictive control (**data-driven modeling**) (Armstrong et al. 2006a; Gayeski et al. 2012; Kraft 2010).

1. GENERAL CONSIDERATIONS

1.1 MODELS AND APPROACHES

A mathematical **model** is a description of the behavior of a system. It is made up of three components (Beck and Arnold 1977):

- **Input variables** (statisticians call these *regressor variables*, whereas physicists call them *forcing variables*), which act on the system. There are two types: controllable by the experimenter (e.g., internal gains, thermostat settings), and uncontrollable (e.g., climate).
- **System structure and parameters/properties**, which provide the necessary physical description of the system (e.g., thermal mass or mechanical properties of the elements).
- **Output** (*response*, or *dependent*) variables, which describe the reaction of the system to the input variables. Energy use is often a response variable.

The science of mathematical modeling as applied to physical systems involves determining the third component of a system when the other two components are given or specified. There are two broad but distinct approaches to modeling: forward (classical) and data driven (inverse). The choice of approach is dictated by the objective or purpose of the investigation (Rabl 1988).

Forward (Classical) Approach

The objective is to predict the output variables of a specified model with known structure and known parameters when subject to specified input variables. To ensure accuracy, models have tended to become increasingly detailed. This approach presumes knowledge not only of the various natural phenomena affecting system behavior but also of the magnitude of various interactions (e.g., effective thermal mass, heat and mass transfer coefficients). The main advantage of this approach is that the system need not be physically built to predict its behavior. The forward-modeling approach is ideal in the preliminary design when design details are limited.

Forward modeling of building energy use begins with a physical description of the building system or component of interest. For example, building geometry, geographical location, physical characteristics (e.g., wall material and thickness), type of equipment and operating schedules, type of HVAC system, building operating schedules, plant equipment, etc., are specified. The peak and average energy use of such a building can then be predicted or simulated by the forward-simulation model. The primary benefits of this method are that it is based on sound engineering principles and has gained widespread acceptance by the design and professional community. Major simulation codes, such as DOE-2, EnergyPlus, ESP-r, and TRNSYS are based on forward-simulation models.

Although procedures for estimating energy requirements vary considerably in their degree of complexity, they all have three common elements: calculation of (1) space load, (2) secondary equipment load and energy requirements, and (3) primary equipment energy requirements. Here, *secondary* refers to equipment that distributes the heating, cooling, or ventilating medium to conditioned spaces, whereas *primary* refers to central plant equipment that converts fuel or electric energy to heating or cooling effect.

The space load is the amount of energy that must be added to or extracted from a space to maintain thermal comfort. The simplest procedures assume that the energy required to maintain comfort is only a function of the outdoor dry-bulb temperature. More detailed methods consider humidity, solar effects, internal gains, heat and moisture storage in walls and interiors, and effects of wind on both building envelope heat transfer and infiltration. The section on Thermal Loads Modeling addresses some of these factors. ASHRAE Standard 183 and Chapters 17 and 18 discuss load calculation in detail.

Although energy calculations are similar to the heating and cooling design load calculations used to size equipment, they are not the same. Energy calculations are based on average use and typical weather conditions rather than on maximum use and worst-case weather. Currently, most procedures are based on hourly profiles for climatic conditions and operational characteristics for a number of typical days of the year or on 8760 hours of operation per year.

The space load is converted to a load on the secondary equipment. This can be a simple estimate of duct or piping losses or gains, or a complex hour-by-hour simulation of an air system, such as variable-air-volume with outdoor-air cooling. This step must include calculation of all forms of energy required by the secondary system (e.g., electrical energy to operate fans and/or pumps, energy in heated or chilled water).

The secondary equipment load is converted to the fuel and energy required by the primary equipment and the peak demand on the utility system. It considers equipment efficiencies and part-load characteristics. It is often necessary to keep track of the different forms of energy, such as electrical, natural gas, and/or oil. In some cases, where calculations are required to ensure compliance with codes or standards, these energies must be converted to source energy or resource consumed, as opposed to energy delivered to the building boundary.

Previously, the steps were performed independently: each step was completed for the entire year and hourly results were passed to the next step. Current software usually performs all steps at each time interval, allowing effects such as insufficient plant capacity to be reflected in room conditions.

Often, energy calculations lead to an economic analysis to establish the cost effectiveness of efficiency measures (as in ASHRAE

The preparation of this chapter is assigned to TC 4.7, Energy Calculations.

19.1

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EARLY DAYS OF SIMULATION IN US – NBSLD 1970S

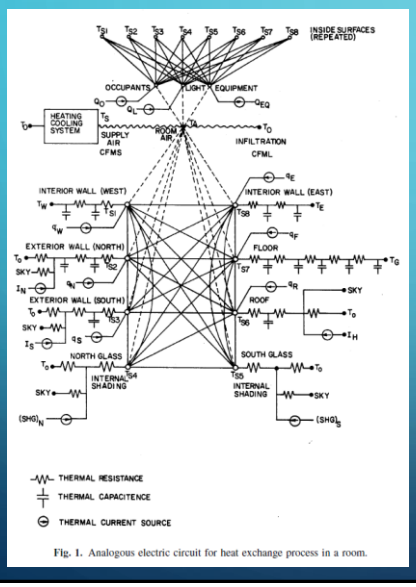

Fig. 1. Analogous electric circuit for heat exchange process in a room.

Walton 2001

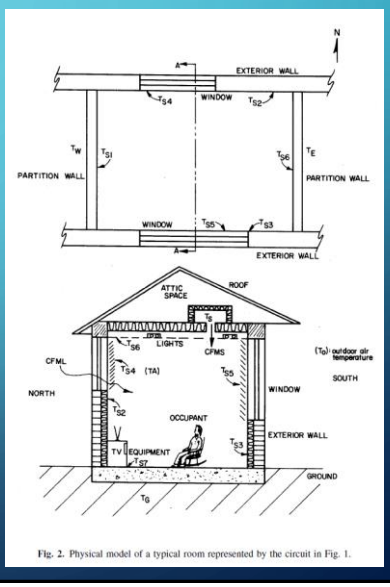

Fig. 2. Physical model of a typical room represented by the circuit in Fig. 1.

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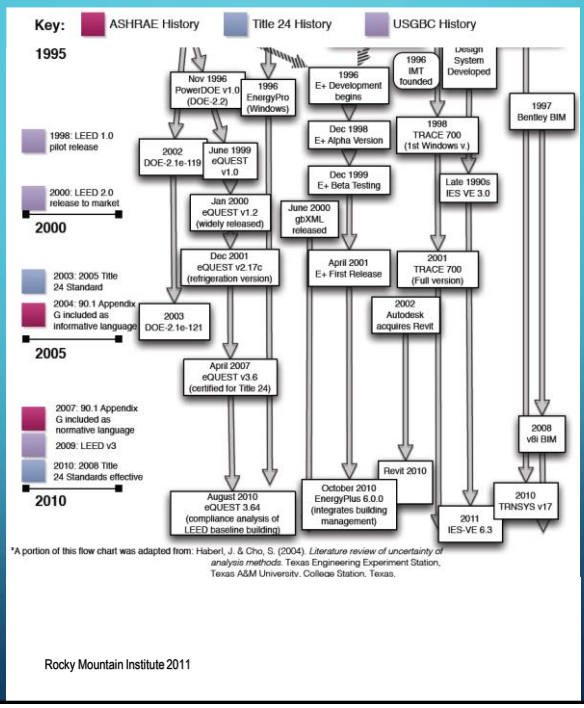

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SIMULATION METHODS FAMILIES

- **Weighting Factors/Transfer Functions**
  - Fast but limited
- **Heat Balance**
  - More accurate but longer computation
- **Thermal Network**
  - Accurate, flexible, long computation

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WEIGHTING FACTOR

- **Weighting factors convert heat gains through building surfaces to heating or cooling loads in a zone. Often pre-calculated at simulation startup**
- Uses combined radiative/convective heat transfer coefficient, which limits accurate simulation of radiant systems.
- Combined coefficients and implicit assumption of constant convective coefficients may compromise accurate prediction of uncontrolled (floating) room air temperatures.
- Temperature prediction problems (e.g., overheating analysis, natural ventilation design) better suited to other methods
- Fast but does not allow varying material properties (PCMs)
- DOE-2.1E, eQUEST/DOE-2.2, IES VE, ~~HAP, TRACE~~

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HEAT BALANCE

- **Calculates conductive, convective, and radiative heat balance for all room surfaces in the thermal zone**
- Fewer assumptions make it more flexible and physically rigorous than the weighting-factor method
- Explicitly calculates radiant energy separately – more accurate temperature and humidity
- Requires more calculations in the simulation process (more computer time)
- Calculates convection conditions at runtime
- BLAST, ASHRAE RTS cooling loads, EnergyPlus, TRNSYS, Trace, HAP

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THERMAL NETWORK

- **Explicit thermal network matrix to represent all heat and energy flows**
- Few assumptions make it flexible and physically rigorous. Requires more explicit input and description of all networks
- Requires more calculations in the simulation process (more computer time)

- ESP-r, IDA ICE

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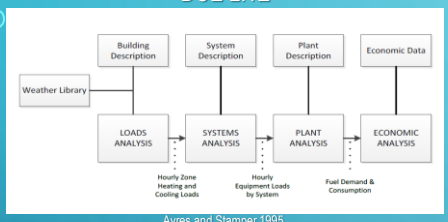
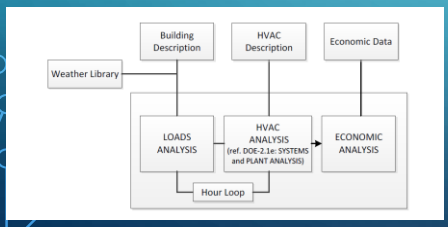
OTHER DIFFERENCES—TIME STEP INTEGRATION

DOE-2.1E



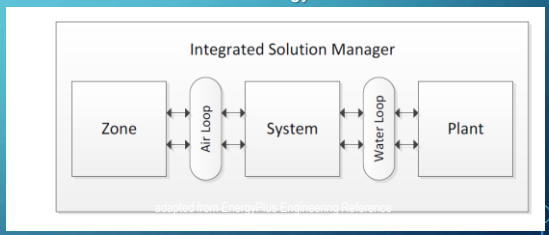
Ayres and Stamper 1995

DOE-2.2



Lawrence Berkeley National Laboratory 1998

EnergyPlus



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DAYLIGHT/LIGHTING SIMULATION

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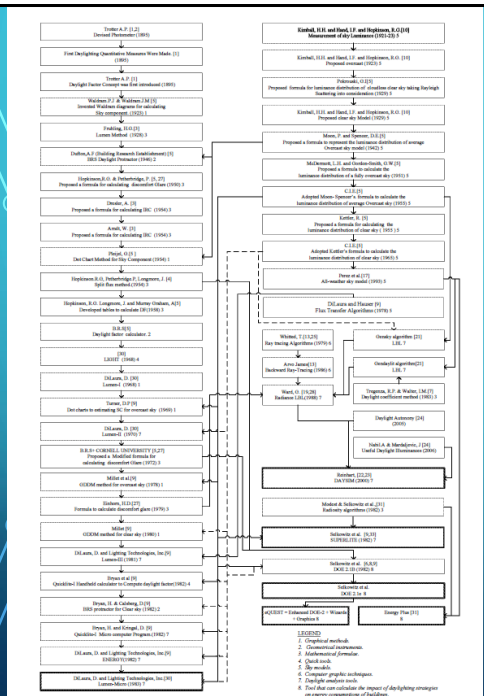

HISTORY OF DAYLIGHTING METHODS

Oh 2013

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MAJOR LIGHTING CALCULATION METHODS

- **Split-Flux**
  - Accurate for simple configurations, fast computation time
- **Radiosity**
  - Accurate for typical configurations, fast computation time, does not account for translucent, transparent or specular surfaces.
- **Ray-Tracing**
  - Accurate for almost all scenarios, can be used to create photorealistic images, slow computation time

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SPLIT-FLUX

- **Calculates Daylight Factor based on the sum of three components: Sky Component (SC) + Externally Reflected Component (ERC) + Internally Reflected Component (IRC)**
- **Strengths:** Accurate for very simple scenarios, fast computation time.
- **Limitations:** Averaged single value for entire zone, does not consider multiple internal reflections (underestimates indirect lighting), does not model specular reflections.
- EnergyPlus, DOE-2.1E, eQUEST, Ecotect

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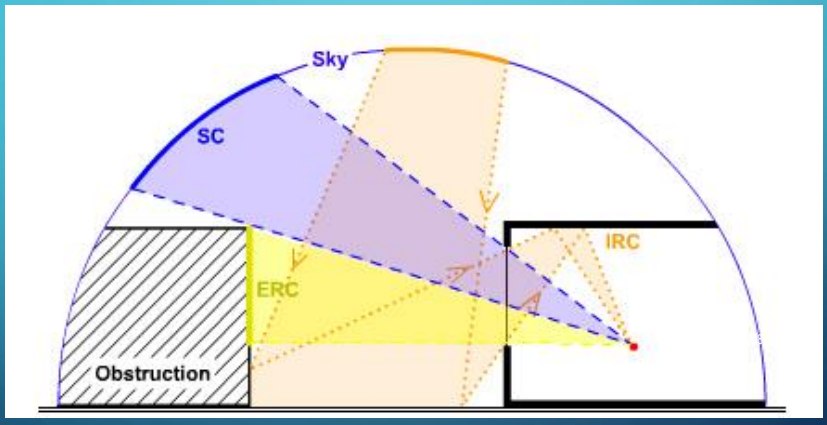
SPLIT-FLUX



DF = SC + ERC + IRC

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RADIOSITY

- **Calculates the radiation transfer among surfaces in a scene to determine light performance in its radiant form**
- **Strengths:** Accurate for most/typical scenarios, can be combined with split-flux to increase accuracy of interior reflection calculations, fast computation time, can be used to create view-based imagery (non-photorealistic).
- **Limitations:** Does not account for light contributions from translucent, transparent or specular surfaces.
- DIALux, DELight (EnergyPlus), AGI32

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RADIOSITY

www.elumtools.com

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RAY-TRACING

- **Point-specific lighting calculation** that follows a given resolution of rays outwards to light sources in a scene
- **Strengths**: Very **accurate** for almost all scenarios, can be used to create photorealistic images.
- **Limitations**: **Slow computation** time

- Radiance, SPOT, Daysim, DIVA

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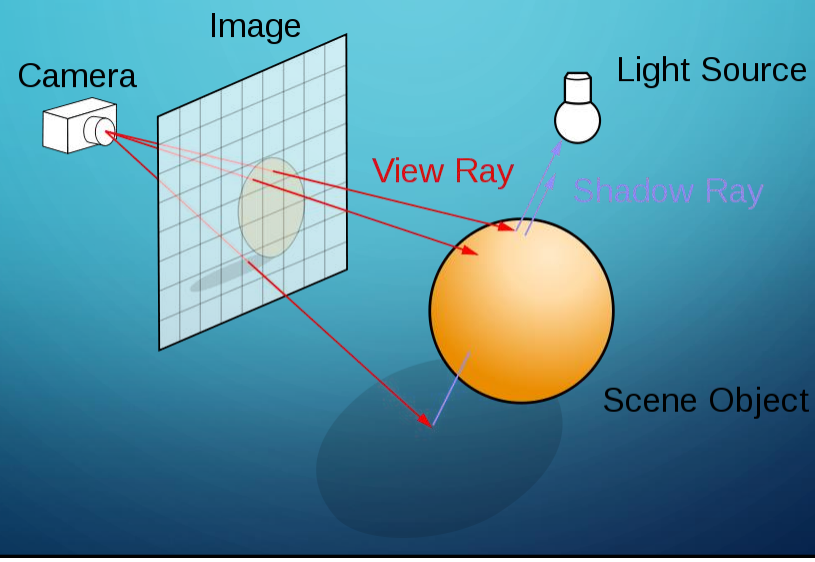
RAY-TRACING



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RAY-TRACING

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RAY-TRACING

ESRU 2005

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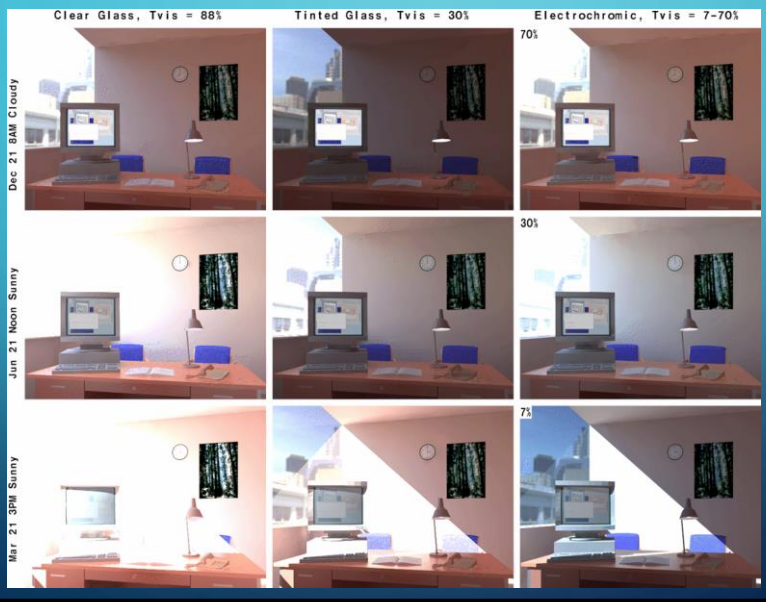
RAY-TRACING GLARE GLAZING STUDIES



LBNL 2007

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SO MANY TOOLS…
WHERE DO I LEARN MORE?

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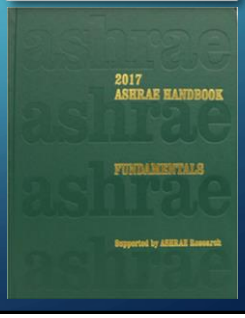
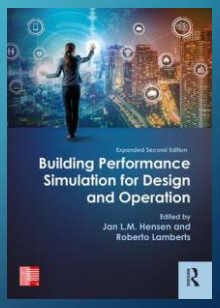
SIMULATION RESOURCES

- Methods and Techniques:
  - *ASHRAE Handbook 2017 Fundamentals*
    Chapter 19 Energy Estimating and Modeling Methods
  - *Building Performance Simulation for Design and Operation*
  - *Contrasting the Capabilities of Building Energy Performance Simulation Programs*

- Available Tools:
  - Building Energy Software Tools Directory
    www.buildingenergysoftwaretools.com





Hensen and Lamberts 2019

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GENERAL MODELING FEATURES

Table 1 General Modeling Features	BLAST	BSim	DeST	DOE-2.1E	ECOTECT	Ener-Win	Energy Express	Energy-10	EnergyPlus	eQUEST	ESP-r	HAP	HEED	IDA ICE	IES <VE>	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
Simulation solution																				
▪ Sequential loads, system, plant calculation without feedback	X			X															X	
▪ Simultaneous loads, system and plant solution	X[2]	X	X		[3]	X	X	X[4]	X	X[5]	X	X[6]	X	X	X	X	X[5]	X		X
▪ Iterative non-linear systems solution		X			[3]			X	X		X	X	X	X	X	X		X	X	X
▪ Coupled loads, systems, plant calculations		X					X	X[4]	X	X	X		X	X	X	X	X			X
▪ Space temperature based on loads-systems feedback	X	X	X		X[6]	X	X	X	X		X	X	X	X	X	X	X	X	X	X
▪ Floating room temperatures[7]	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Time step approach																				
▪ User-selected for zone/environment interaction	X[2]	X[10]	R					X[11]	X[12]		X[13]			X	X	X[14]	X			X[13]
▪ Variable time intervals for zone air/HVAC system interaction	X[2]	X[10]					X		X	X[16]	X				R					
▪ User-selected for both building and systems											X			X	X	X				X[17]
▪ Dynamically varying based on solution transients									X		X			X[18]						
Full Geometric Description																				
▪ Walls, roofs, floors	X	X	X	X	X	X	X		X	X	X		X	X	X	X	X	X	X	X[19]
▪ Windows, skylights, doors, and external shading	X	X	X	X	X	P	X		X	X	X		X	X[20]	X	X	X	X	X	X

[2] Only in IBLAST, an unreleased, integrated simulation version of BLAST. BLAST simultaneously calculates all zones in the "building" heat balance.
[3] ECOTECT exports its models to the native file formats of EnergyPlus, ESP-r, HTB-2, and Radiance, invoking calculations and then importing results for display and analysis.
[4] CNE simulation engine used by Energy-10 uses iterative convergence to achieve energy balance (thermal network coupled with building systems) at each time step.
[5] HVAC air-side and water-side combined calculation
[6] Loads and HVAC airside systems integrated with feedback. Plant is sequential with system loads.
[7] Idealized HVAC equipment only in release version. Research version with more realistic HVAC models.
[8] Based on CIBSE Admittance Method for early design decision-making and analysis
[9] No environmental controls
[10] Up to 256 timesteps per hour
[11] For Energy-10 the CNE engine runs in 15-minute time steps with results reported on an hourly basis.
[12] 15-minute default, 10 minute to 1 hour time steps. Use can modify so that 1 minute time steps can be done but not recommended due to stability issues.
[13] 1 minute to 1 hour time steps for zones and flow networks and a multiple of that for detailed systems.
[14] 1-hour default, 1-second to 24-hour time steps. 1-minute time interval schedules.
[15] Building and system use the same time step. 1-hour default, user can select down to 0.1 second
[16] 5 minute time step for electric heat/cool/fan equipment for demand vs. energy cost calculation
[17] Type 56 (building) uses an internal time step for airflow and envelope coupling. Other components (e.g. storage tanks) have internal time steps
[18] User-specified tolerance controls time step and integration order
[19] Taking into account geometry for view factors, detailed shading, direct radiation distribution requires additional input data.
[20] Skylights with multiple beam reflections

ZONE LOADS AND ENVELOPE

Table 1 Zone Loads (11 of the 18 rows in the report)	BLAST	Bsim	DOE-2.1E	Ecotect	Energy-10	EnergyPlus	Ener-Win	eQUEST	ESP-r	IDA IES	IES <VE>	HAP	HEED	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
Interior surface convection																		
• Dependent on temperature	X	X				X			X				X	X	X	X		X
• Dependent on air flow	X					P			X		X		X			X		E
• Dependent on surface heat coefficient from CFD									E		X							
• User-defined coefficients		X				X			E		X		X	X	X	X		X
Internal Thermal Mass	X	X	X	X		X		X	X		X		X	X	X	X	X	X
Automatic design day calculations for sizing																		
• Dry bulb temperature	X	X	X	X	X	X		X				X	X	P		X	X	
• Dew point temperature or relative humidity						X		X				X				X	X	
• User-specified minimum and maximum						X		X				X	X			X		
• User-specified steady-state, periodic or dynamic design conditions																X		X

Table 2 Building Envelope and Daylighting (10 of the 54 rows in the report)	BLAST	BSim	DOE-2.1E	Ecotect	Energy-10	EnergyPlus	Ener-Win	eQUEST	ESP-r	IDA ICE	IES <VE>	HAP	HEED	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
▪ Outside surface convection algorithm																		
▪ BLAST/TARP	X					X											X	
▪ DOE-2			X			X		X									X	
▪ MoWiTT						X			X								X	
▪ ASHRAE simple	X				X	X							X			X	X	
▪ User-selectable						X			X		X			X		X	X	X
▪ Inside radiation view factors		X				X			X							X		
▪ Radiation component separate from convection		X				X		X	X		X					X	P	X
▪ Detailed solar and daylighting inter-reflection from building components and other buildings		P		X		X			X		X							X
▪ Shading of sky IR by obstructions			X			X		X			X					X		X

AIRFLOW, HVAC AND ECONOMICS

Table 4 ***Infiltration, Ventilation, Room Air and Multizone Airflow***	BLAST	BSim	DOE-2.1E	Ecotect	Energy+ 10	EnergyPlus	Ener-Win	eQUEST	ESP-r	IDA ICE	IES <VE>	HAP	HEED	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
Single zone infiltration	X	X	X	X	X	X		X			X	X	X	X	X	X	X	X
Automatic calculation of wind pressure coefficients		X				X					X				X	X		
Natural ventilation (pressure, buoyancy driven)		X				X		X	X		X			X	X	X		O
Multizone airflow (via pressure network model)		X				X			X		X				X	X		O
Hybrid natural and mechanical ventilation		X							I		X					X		O
Control window opening from simulation variables						X					X							O
Displacement ventilation						X			X		X					X		O
Mix of flow networks and CFD domains									E									
Contaminants, microtoxins (mold growth)		P							R					P				

Tables 7 & 8 ***HVAC Systems and components*** ***(summary)***	BLAST	BSim	DOE-2.1E	Ecotect	Energy+ 10	EnergyPlus	Ener-Win	eQUEST	ESP-r	IDA ICE	IES <VE>	HAP	HEED	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
Idealized HVAC systems	X			X		X			X									X
User-configurable HVAC systems		X				X			X		X	X	X	X	R	X		X
Pre-configured systems (among 32 identified, X+O)	14	14	15	0	7	30	ND	24	13	ND	24	26	10	9	11	23	21	20
Discrete HVAC components (among 98 identified, X+O)	59	24	43	0	11	72	ND	59	26	ND	33	41	7	21	13	26	57	80

Table 11 ***Economic Evaluation*** ***(energy costs portion)***	BLAST	BSim	DOE-2.1E	Ecotect	Energy+ 10	EnergyPlus	Ener-Win	eQUEST	ESP-r	IDA IES	IES <VE>	HAP	HEED	PowerDomus	SUNREL	Tas	TRACE	TRNSYS
Energy Costs																		
• Simple energy and demand charges		X	X	X	X	X		X	X		X	X	X	X		X	X	X
• Complex tariffs including fixed, block, and demand charges, ratchets		X	X			X		X			X	X	X				X	E
• Scheduled variation in all rate components		X	X			X		X			X	X	X			X	X	X
• User selectable billing dates			X			X		X					X				X	E

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NEXT GENERATION REPORT UNDER DEVELOPMENT

- Tools we missed?
- How can we make it clearer?
- What else do you want to see?
- Ultimately—dynamic web-based resource linked to each tool with example input files for each capability as well as the suite of validation inputs.
- Already underway—making testing results (and inputs) available, including solution methods and much more.

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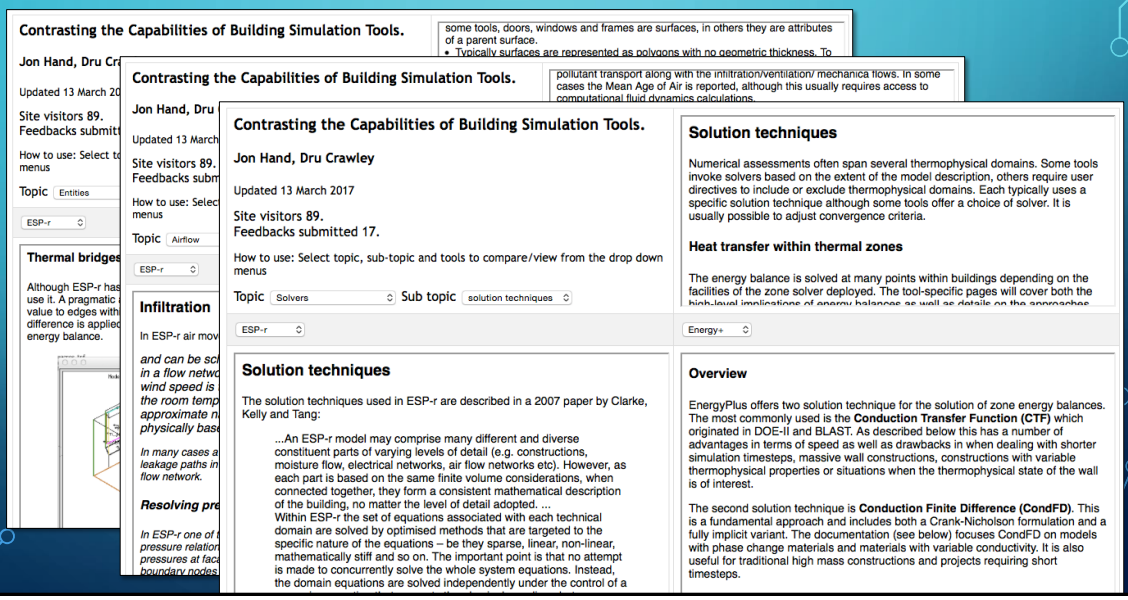
CONTRASTING WHITE PAPER → WEB SITE



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TESTING AND VALIDATION

You need to know:

- Is the simulation program fully tested using industry standards:
  - ANSI/ASHRAE Standard 140 *Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs*
  - IEA BESTEST
  - ISO/EU
- Where are the test inputs and results?
- LEED, Title 24, 90.1, 189.1, IECC, IGCC, and other systems require testing be performed using ASHRAE Standard 140

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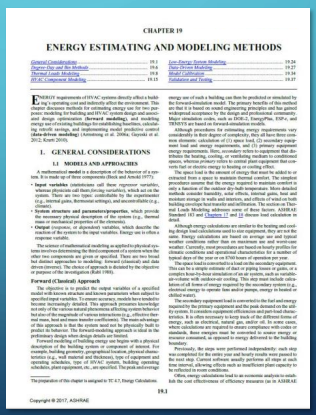
WHAT SHOULD I LOOK FOR IN PERFORMANCE SIMULATION TOOLS?

- Accuracy
- Sensitivity
- Versatility
- Speed and cost
- Reproducibility
- Ease of Use
- Validation



CHAPTER 19

ENERGY ESTIMATING AND MODELING METHODS

General Considerations 19.1
Degree-Day and Bin Methods 19.4
Thermal Load Modeling 19.8
HVAC Component Modeling 19.15
Low-Energy System Modeling 19.24
Data-Driven Modeling 19.27
Model Calibration 19.34
Validation and Testing 19.37

ENERGY requirements of HVAC systems directly affect a building's operating cost and indirectly affect the environment. This chapter discusses methods for estimating energy use for two purposes: equipment sizing for design loads, and annual energy use and design optimization (**forward modeling**), and modeling energy use of existing buildings for establishing baselines, calculating retrofit savings, and implementing real-time predictive control (**data-driven modeling**) (Armstrong et al. 2004a; Tajevski et al. 2012; Kusiv 2010).

1. GENERAL CONSIDERATIONS

1.1 MODELS AND APPROACHES

A mathematical model is a mathematical description of a system. It is made up of three components (Hauck and Arnold 1977):

- **Input variables** (statisticians call these *regressor variables*, whereas physicists call them *forcing variables*), which act on the system. There are two types: controllable by the experimenter (e.g., internal gains, thermostat settings), and uncontrollable (e.g., weather).
- **System structure and parameters/properties**, which provide the necessary physical description of the system (e.g., thermal mass or mechanical properties of the elements).
- **Output variables** (*response variables*), which describe the reaction of the system to the input variables. Energy use is often a response variable.

The science of mathematical modeling as applied to physical systems involves determining the third component of a system when the first two components are known. Several fields have developed two distinct approaches to modeling, forward (classical) and data-driven (inverse). The choice of approach is dictated by the objective or purpose of the investigation (Kubi 1980).

Forward (Classical) Approach

The objective is to predict the output variables of a specified model with known structure and known parameters when subject to specified input variables. To ensure accuracy, models have tended to become increasingly detailed. This approach promotes knowledge of the physical behavior of subsystems and their components (e.g., the nature of the magnitude of various interactions (e.g., effective thermal mass, heat and mass transfer coefficients). The main advantage of this approach is that it can be used to study new designs that predict its behavior. The forward-modeling approach is ideal in the preliminary design when design details are limited.

Forward modeling of building energy use begins with a physical description of the building system or component of interest. For example, the mathematical description of a building envelope characteristics (e.g., wall material and thickness), type of equipment and operating schedules, type of HVAC system, building operating schedules, plant equipment, etc., are specified. The peak and/or average energy use of such a building can then be predicted or simulated by the forward-simulation model. The primary benefits of this method are that it is based on sound engineering principles and has gained widespread credibility for a wide variety of building energy problems. Major simulation codes, such as BSIC2, EnergyPlus, ESP-r, and TRNSYS are based on forward-simulation models.

Buildings and their HVAC systems and energy requirements vary considerably in their degree of complexity. Here all have three common elements: calculation of (1) space load, (2) secondary equipment load and energy requirements, and (3) primary equipment energy requirements. Here, *secondary* refers to equipment that directly serves the space (i.e., transfers energy to or from conditioned spaces, whereas *primary* refers to central plant equipment that converts fuel or electric energy to heating or cooling effect.

The space load is the rate at which energy must be added to or removed from a space to maintain desired thermal comfort. The simplest methods assume that the space load required to maintain comfort is only a function of the outdoor dry-bulb temperature. More detailed methods consider humidity, solar effects, internal gains, heat and moisture storage effects, and dynamic response. Chapter 18 covers the building envelope heat transfer and infiltration. The section on Thermal Load Modeling addresses some of these factors. ASHRAE Standard 183 and Chapters 17 and 18 discuss load calculation in detail.

Although energy calculations are similar to the heating and cooling design load calculations used to size equipment, they are not the same. Energy calculations are based on average use and typical weather conditions, whereas design loads are based on extreme weather. Currently, most procedures are based on hourly profiles for climatic conditions and operational characteristics for a number of typical days of the year or on 8760 hours of operation per year.

The space load is converted to a load on the secondary equipment, which is the HVAC equipment that directly serves the space. For a complete hour-by-hour simulation of an air system, such as variable-air-volume with outdoor-air cooling. This step must include calculation of the quantities of energy required by the secondary system (e.g., electrical energy to operate fans and/or pumps, energy to heated or chilled water).

The secondary equipment load is converted to the fuel and energy required by the primary equipment and the peak demand on the utilities serving the building (electrical power, natural gas, and/or oil) over periods. It is often necessary to keep track of the different forms of energy, such as electrical, natural gas, and/or oil. In some cases, where calculations are required to ensure compliance with codes or standards, these energies must be converted to source energy at the point consumed, as opposed to energy delivered to the building boundary.

Previously, the steps were performed independently: each step was completed for the full design year and hourly results were passed to the next step. Current software usually performs all steps at each time interval, allowing effects such as insufficient plant capacity to be reflected in room conditions.

Often, energy calculations lead to an economic analysis to establish the cost effectiveness of efficiency measures (as in ASHRAE

The preparation of this chapter is assigned to TC 4.7, Energy Calculations.

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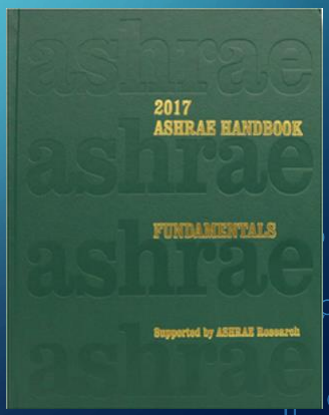

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HOW DO I DECIDE WHICH BUILDING PERFORMANCE TOOL(S) TO USE?

- What are you trying to assess?
  - Simple change in performance may warrant a simpler tool – such as bin method or degree-day
  - Interactions among building systems often warrants dynamic simulation tools
- Make sure the tool can predict the physics you're interested in, such as radiant systems, daylight illuminance, ground heat transfer, or a specific HVAC system configuration

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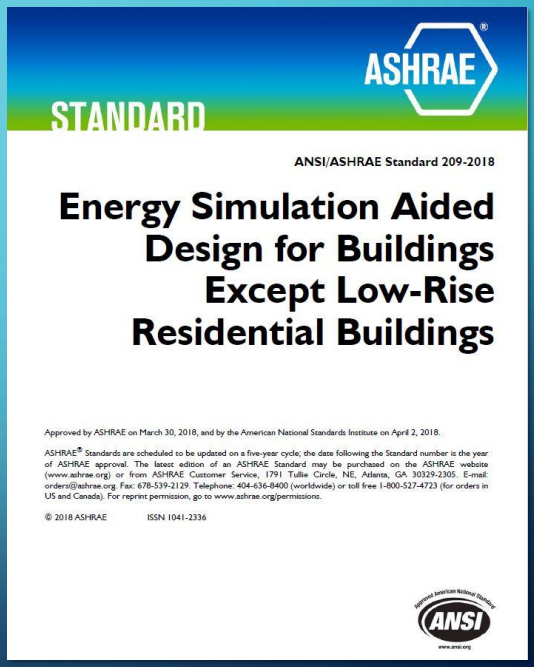
STANDARD 209


STANDARD

ASHRAE

ANSI/ASHRAE Standard 209-2018

Energy Simulation Aided Design for Buildings Except Low-Rise Residential Buildings

Approved by ASHRAE on March 30, 2018, and by the American National Standards Institute on April 2, 2018.

ASHRAE® Standards are scheduled to be updated on a five-year cycle; the date following the Standard number is the year of ASHRAE approval. The latest edition of an ASHRAE Standard may be purchased on the ASHRAE website (www.ashrae.org) or from ASHRAE Customer Service, 1791 Tullie Circle, NE, Atlanta, GA 30329-2305. E-mail: orders@ashrae.org. Fax: 678-539-2129. Telephone: 404-636-8400 (worldwide) or toll free 1-800-527-4723 (for orders in US and Canada). For reprint permission, go to www.ashrae.org/permissions.

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ANSI

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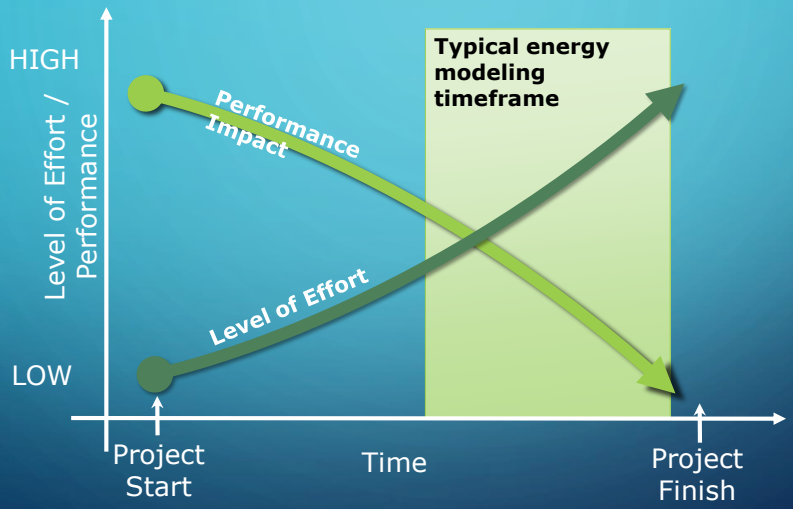
WHEN DO WE USE ENERGY MODELING?



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TITLE, PURPOSE, AND SCOPE

Title:

- Energy Simulation Aided Design for Buildings Except Low-Rise Residential Buildings

Purpose:

- **Define minimum requirements for providing energy design assistance using building energy simulation and analysis.**

Scope:

- This standard applies to new buildings or major renovations of, or additions to, existing buildings utilizing energy simulation during the design process. This standard does not apply to single-family houses, multi-family structures of three stories or fewer above grade, manufactured houses (mobile homes) and modular homes.

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WHO COMPLIES?

- *NOT* required for all buildings
- "utilizing energy simulation during the design process"
- For adoption by:
  - Organizations that certify high performance buildings
  - Utilities and agencies that provide incentives for low energy buildings
  - Building owners and architects seeking a uniform way to specify a scope of work for building energy modeling.

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COMPLIANCE

Required: all of these activities

- 5.3 Climate and Site Analysis
- 5.4 Benchmarking
- 5.5 Energy Charrette
- 5.6 Energy Performance Goals in OPR
- 5.7 General Modeling Cycle Requirements + 6.3 Modeling Cycle #3 Load Reduction Modeling

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COMPLIANCE

Required: one of the following

- 5.7 + 6.1 Modeling Cycle #1 – Simple Box Modeling
- 5.7 + 6.2 Modeling Cycle #2 – Conceptual Design Modeling
- 5.7 + 6.4 Modeling Cycle #4 – HVAC System Selection Modeling
- 5.7 + 6.5 Modeling Cycle #5 – Design Refinement
- 5.7 + 6.6 Modeling Cycle #6 – Design Integration and Optimization
- 5.7 + 6.7 Modeling Cycle #7 – Energy Simulation Aided Value Engineering

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WHAT ABOUT CREATING MY BUILDING SIMULATION MODEL FROM BIM?

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BIM? SIM?

- BIM – Building Information Model/Modeling
  - Represent building as 3-d objects: geometry, spatial relationships, geographic information, and building components properties.
  - Graphic, interactive models.
  - Can be robust and rich source of building data – if the data are entered.
- Sim – Building Performance Simulation
  - Modeling building energy/environmental performance.
  - Used in building design or retrofit to reduce energy use and environmental impact.

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BUILDING INFORMATION MODEL/MODELING

- Building Information Model:
  - Digital representation of physical and functional characteristics of a facility. . . shared knowledge resource for information about a facility, forming a reliable basis for decisions during its life cycle from inception onward.[1]
- Building Information Modeling:
  - Using BIM software and other related software, hardware and technologies in a building information model.[2]

- 1 NIBS 2015
- 2 Jernigan 2007

→ ***Information Mobility***

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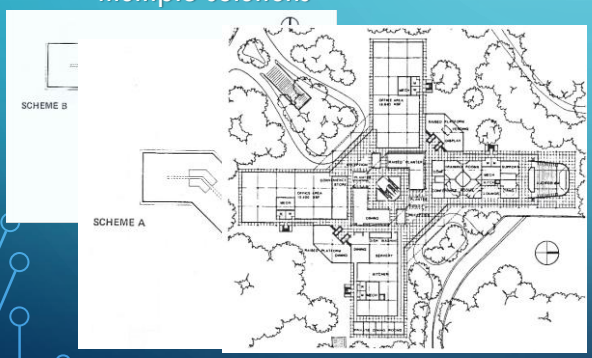
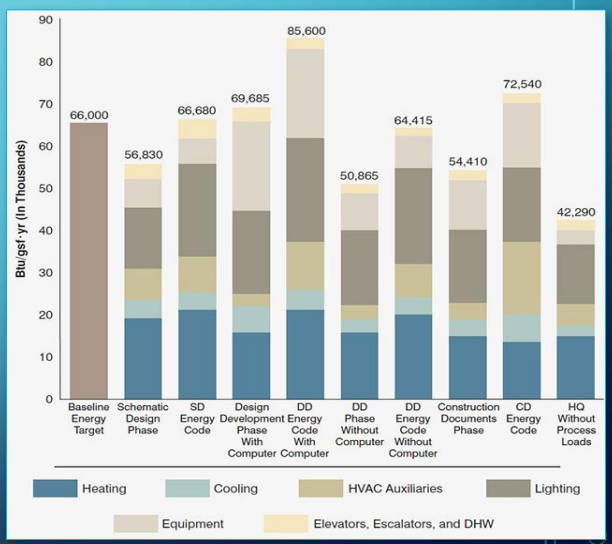
TRADITIONAL SIMULATION WORKFLOW CHALLENGES

- Early design through construction documents – with increasing detail, multiple solutions





Nall and Crawley 2011

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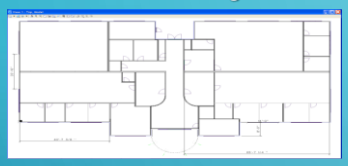
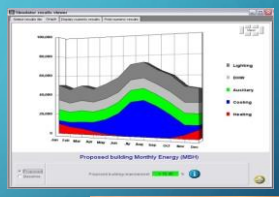
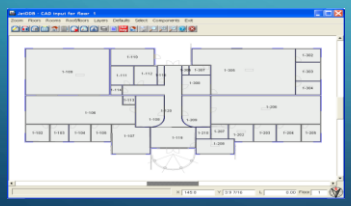
2D WORKFLOW

2-D Drawing

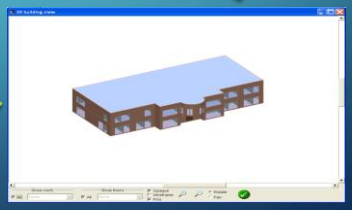


Analysis Results





Define Spaces



Energy Model

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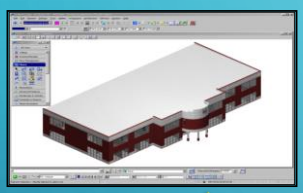
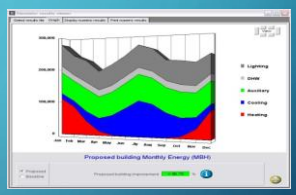
BIM TO SIM (IN)DIRECTLY

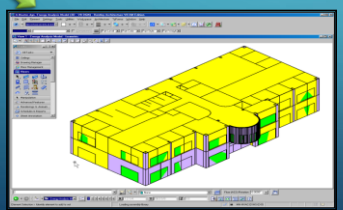
BIM Model

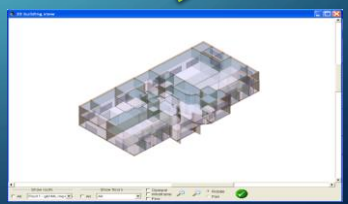


Analysis Results



Analytical Model





via gbXML, IFCs, direct

Energy Model

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BIM TODAY IS NOT YOUR FATHER'S CAD

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BIM TO SIM(ULATION)

- Translate BIM to Simulation
  - BuildingSMART IFCs (Industry Foundation Classes)
    - Any BIM software that supports interoperability, available since 2001
    - Limited to what BIM tools decide to export—typically only geometry
  - gbXML
  - Autodesk Green Building Studio
    - Web-based conversion of major BIM formats to energy simulation inputs
    - Limited coverage
    - Can require users to create their BIM drawings in structured way (may not follow designer regular workflow)
- Direct from BIM to Simulation
  - Major BIM tools have built-in simulation or directly export to one or more simulation tools
- Interoperability is key to getting energy simulation mainstream. Other drivers—zero-energy buildings and green building rating systems

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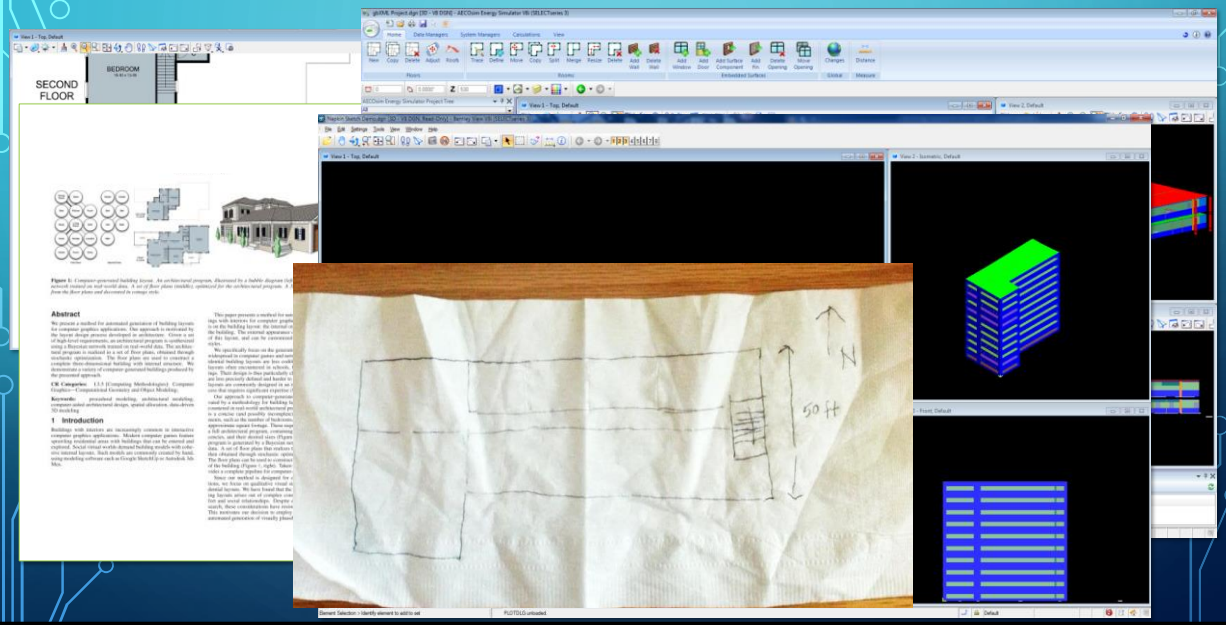
2-D, 3-D, PDF BIM TO SIM



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THE CHALLENGE OF SIMULATING EXISTING BUILDINGS

- Existing building often means no 3-D model, maybe no drawings at all
- Drawings often are design or construction – not as-built
- Result?
  - Takeoffs from drawings
  - Field verification/measurements
  - Manual translation/interpretation of data
  - Lots of time better spent evaluating alternatives

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NEW MODELING TECHNOLOGIES AVAILABLE

- LiDAR (Light and raDAR)
  - Remotely measures distance by illuminating a target with a laser and analyzing the reflected light
  - High resolution accuracy but limited density
  - Can be expensive to implement
- Photogrammetry
  - Uses automated triangulation of a series of photographs to mathematically create 3-D meshes or point clouds
  - Depends on quality of photos and fit of triangulation
  - Can be used for creating a 3-D mesh with draped images
  - Works well with aerial drones

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LIDAR

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PHOTOGRAMMETRY

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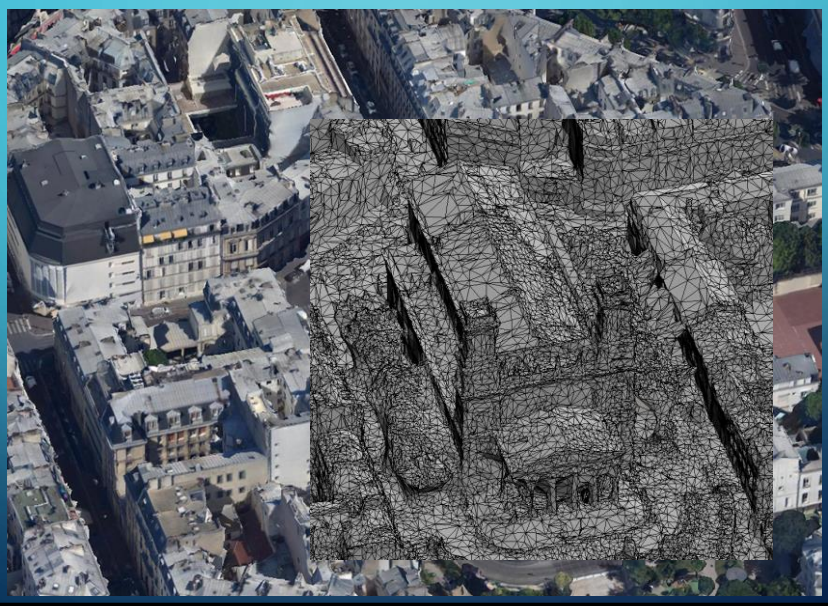
PHOTOGRAMMETRY



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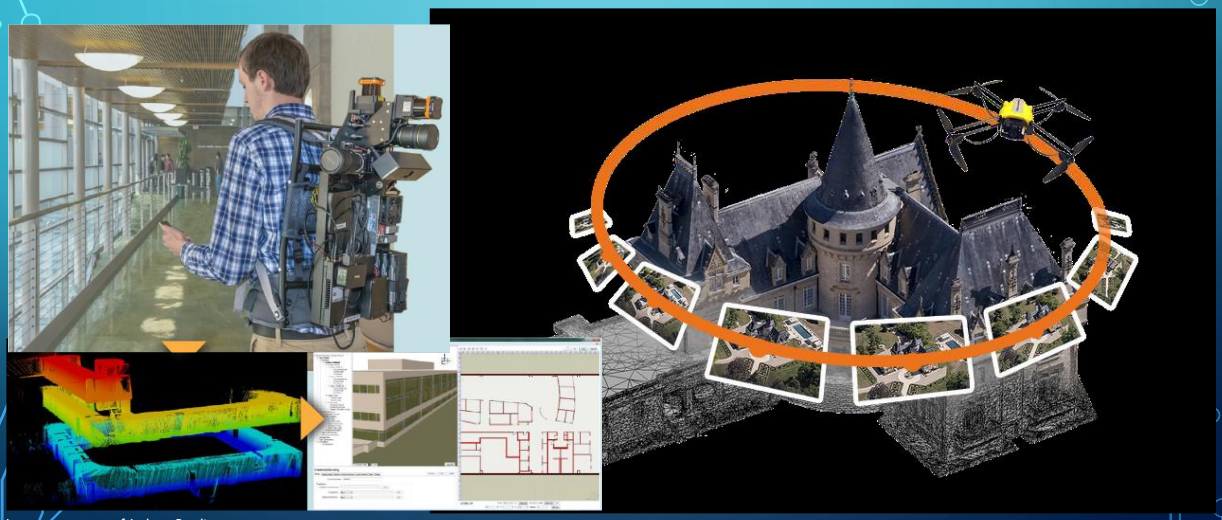
CREATING MODELS FROM PHOTOS OR CAPTURED DATA



Images courtesy of Indoor Reality

Image courtesy of Acute3D

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CAN I GET A MODEL?

- IFCs and gbXML offer easy way to export building geometry. Other data limited.
- LiDAR produces high quality, high resolution models, can be time-consuming (costly) to acquire geometry data
- Photogrammetry requires a great set of photos—good lighting, limited shadows, 70% overlap between photos, with georeferencing camera (GPS and rotation in EXIF) – most Smartphones!
- Mesh and planar data can be easily imported into BIM and energy analysis tools that support BIM
- Yes!

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SUMMARY

- Solution Methods
  - What's in the black box as important, if not more important, than the interface and results.
  - Each solution method useful – simpler ones may be limited for complex building systems and low-energy solutions.
- Acquiring Building Data
  - Getting data from BIM to Sim through interoperability still a significant challenge – often incomplete, insufficient for simulation → blackbox defaults! IFCs and gbXML offer easy way to export building geometry from BIM. Users need to understand the model they're creating. Other data can be limited.
  - LiDAR and photogrammetry offer means to capture existing buildings. Mesh that LiDAR and Photogrammetry create can easily be imported by BIM and energy analysis tools
- Quality of simulation results only as good as the data entered: GIGO – the more data about the building and how it operates the better quality the results.
- Building performance simulation is a powerful tool for evaluating and comparing building systems and technologies throughout the building life-cycle

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SO, ARE THESE TOMORROW'S BUILDINGS?

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PROBABLY MORE LIKE NREL RSF (NZEB)

81

OR THESE RECENT NZE BUILDINGS

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NO SINGLE METRIC TELLS THE BUILDING PERFORMANCE STORY

Energy

Demand

Cost

Water

IEQ

Carbon

Business

(student, occupied room, sales, beer barrels)

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THANK YOU!

QUESTIONS?

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ASHRAE Iowa Chapter

GBCI Approved | 1 CE Hour | 0920010371
AIA Approved | 1 LU/HSW | CRAWLEY07

DruCrawley @DruCrawley Drury_Crawley DrDru.Crawley

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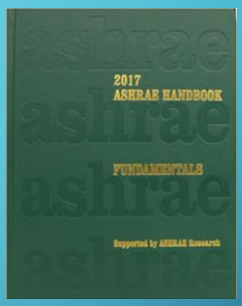
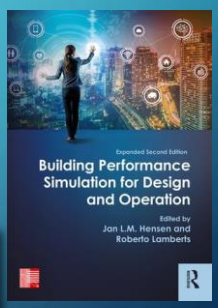
RESOURCES

- ASHRAE Handbook 2017 Fundamentals
  Chapter 19 Energy Estimating and Modeling Methods www.ashrae.org
  www.techstreet.com/ashrae/standards/2017-ashrae-handbook-fundamentals-i-p-includes-cd-in-i-p-and-si-editions?product_id=1975069
- Hensen, Jan L.M. and Roberto Lamberts, editors. 2019. Building Performance Simulation for Design and Operation, second edition. London: Spon Press.
- Crawley, D.B., J. W. Hand, M. Kummert, B.T. Griffith. 2005. Contrasting the Capabilities of Building Energy Performance Simulation Programs. climate.onebuilding.org/papers/2005_07_Crawley_Hand_Kummert_Griffith_contrasting_the_capabilities_of_building_energy_performance_simulation_programs_v1.0.pdf
- Building Energy Software Tools Directory
- www.buildingenergysoftwaretools.com





Hensen and Lamberts 2019

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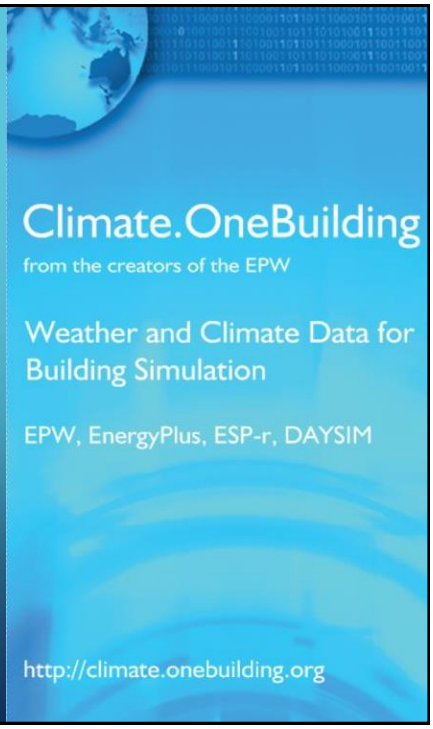
NEED CLIMATE DATA?

- climate.onebulding.org
- Annual and monthly design conditions
- Verified, up-to-date location names:
  - USA_VA_Arlington-Reagan.Washington.National.AP or USA_VA_Dulles-Washington.Dulles.Intl.AP instead of Washington, DC
- Hourly precipitation in a separate file for direct use in simulations (where source data includes precipitation)
- Extensive quality checking to identify and correct data errors and out of normal range values where appropriate.
- EnergyPlus (EPW), DAYSIM/Radiance (WEA), ESP-r (CLM) format files included along with summary statistics and design conditions
- More than 13,500 locations worldwide



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Integrating Energy Modeling in the Design Process

Section 1 – Energy is a Design Problem

Section 2 – Why Should Architects Care about Energy Modeling?

Section 3 – High Performance Design Process

Section 4 – Performance Analysis and Modeling

Section 5 – Current Tools

Section 6 – Our Future Begins Today

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www.aia.org/practicing/AIAB097932

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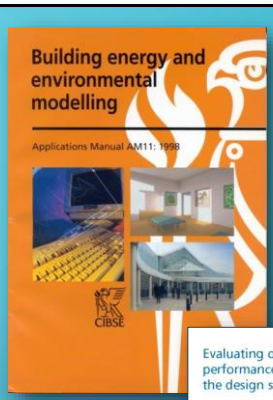
- Building Energy and Environmental Modeling
  www.cibse.org/Knowledge/CIBSE-AM/AM11-Building-Energy-and-Environmental-Modelling

- Evaluating Operational Energy Performance of Buildings at the Design Stage
  www.cibse.org/Knowledge/CIBSE-TM/TM54-Evaluating-Operational-Energy-Performance-of



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