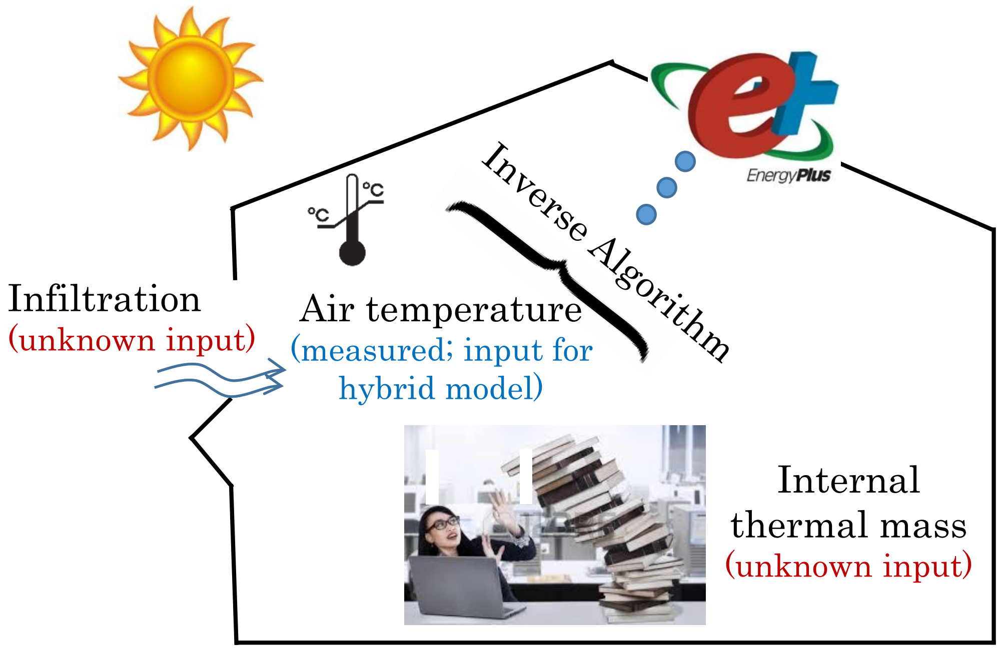
BENEFIT: Hybrid Approach to Energy Modeling

2016 Building Technologies Office Peer Review



Combine physics-based models with widely available measured data
to improve modeling of existing buildings

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

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Project Summary

Timeline:

- Start date: 10/1/2014
- Planned end date: 9/30/2016

Key Milestones

- Algorithm development: 6/30/15
- EnergyPlus implementation: 12/31/15
- Validation: 7/31/16
- EnergyPlus release: 9/30/16

Budget:

- **To Date**: $400,000 (cost share: $50,000)
- **Total:** $600,000 (cost Share: $67,000)

Key Partners:

- California Energy Commission

Project Outcome:

- New EnergyPlus feature that improves simulation of existing buildings
- Feature uses zone temperature time series (i.e., smart thermostat data) instead of hard-to-acquire infiltration and thermal mass inputs
- Complements calibration

Purpose and Objectives

Problem Statement:

- Energy modeling is not just for new construction (code-compliance, LEED), increasingly important for existing buildings (retrofit-planning, re-commissioning, control, etc.).
- Impactful hard-to-get inputs make modeling existing buildings difficult
  - Infiltration: #1 tuning “knob”, difficult for commercial buildings (blower door?)
  - Internal thermal mass: furniture, books, etc. (why libraries are cooler than offices)
- Model input calibration has challenges: over-fitting & multiple solutions.

Target Application and Audience:

- Residential & commercial deep retrofits (*i.e.*, envelope & HVAC), M&V
- ESCOs, large-portfolio owners, utilities, energy consultants

Impact:

- Easier, more accurate modeling for existing buildings
- Improved modeling of HVAC, envelope & DR ECMs

Approach

Approach:

- Leverage readily available data streams (e.g., zone air temperatures from smart thermostats) to calculate infiltration & internal thermal mass inputs
- “Hybrid”: dynamically combines physics & measured data
- Test & validate the hybrid model using:
  - Simulated data: does it work under “ideal” conditions? Is it equivalent to physics?
  - Measured data: leverage FLEXLAB
- Make new feature available in EnergyPlus V8.6 (Sep. 2016)

Key Issues:

- Making this functionality usable

Distinctive Characteristics:

- Focus on improving simulation for existing buildings
- Data integration approach
- Joint model development & validation

Traditional Modeling Workflow

1. Floor area
2. Climate zone
3. **Infiltration**
4. **Roof R-value**
5. **Window R-value**
6. **Thermal Mass**
7. Heating type
8. **Heating efficiency**
9. ...

#1. Initial model

- **Uncertain input**

1. Floor area
2. Climate zone
3. **Infiltration’**
4. **Roof R-value’**
5. **Window R-value’**
6. **Thermal Mass’**
7. Heating type
8. **Heating efficiency’**
9. ...

#2. Optional calibration → improved model

- Utility bills
- Meter/thermostat data

#3. ECMs

1. Floor area
2. Climate zone
3. **Infiltration’**
4. **Roof R-value’**
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Hybrid Modeling Workflow

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9. ...

#1. Initial model

- **Uncertain input**

#2. Hybrid model

- Smart thermostat
- Nail down infiltration & thermal mass

#2. Optional calibration

- Easier to calibrate remaining inputs

#3. ECMs

1. Floor area
2. Climate zone
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4. **Roof R-value'**
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Hybrid Modeling – An Inverse Problem

The zone heat balance equation:

$$\boldsymbol{F} V \rho_{air} C_p \frac{d\boldsymbol{T_z}}{dt} = \sum_j Q_j + \sum_i h_i A_i (T_{si} - T_z) + \sum_i \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_o - T_z) + Q_{sys}$$

Invert the zone heat balance equation and use

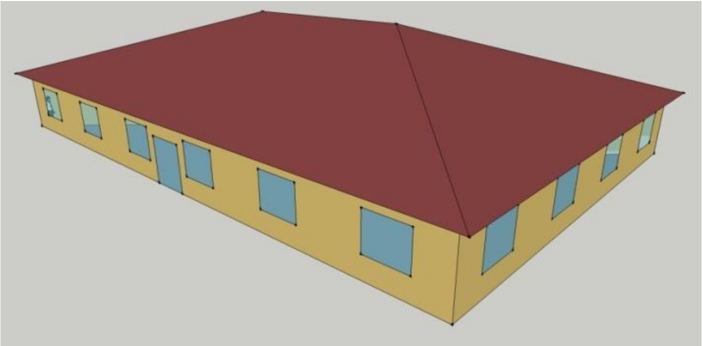
$\boldsymbol{T_z}$ (measured zone air temperature)

to solve:

F (internal mass multiplier) and/or $\dot{\boldsymbol{m}}_{\boldsymbol{inf}}$ (infiltration rate).

$\sum_i h_i A_i (T_{si} - T_z)$	convective heat transfer from the zone interior surfaces
$\sum_j Q_j$	the convective portion of internal heat gains
$\sum_i \dot{m}_i C_p (T_{zi} - T_z)$	heat transfer due to interzone air mixing
Q_{sys}	delivered energy from HVAC systems

Validation I — Simulated Data



What does this prove?

- Hybrid modeling works under ideal conditions
- Is equivalent to physics-based modeling

How do we do this?

- Use known infiltration & thermal mass values
- Generate synthetic zone-temperature stream
- Can hybrid model reliably reconstruct known values?

Setup

- The DOE reference models of the small office buildings
- Four typical climate zones: Miami, San Francisco, Chicago, Fairbanks
- Two vintages: Pre 1980 and 2004
- Five levels of internal thermal mass
- Nine levels of infiltration rates

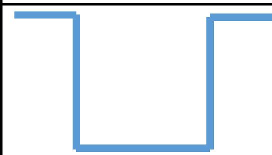
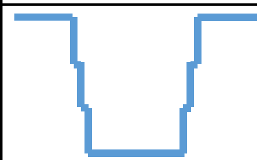
Validation Results for Zone Internal Thermal Mass

Building	Location	Vintage	Zones				
			CORE_ZN	PERIMETER_ZN_1	PERIMETER_ZN_2	PERIMETER_ZN_3	PERIMETER_ZN_4
			User Input of Zone Internal Thermal Mass Multipliers				
			2	5	10	15	20
			EnergyPlus Calculated Zone Internal Thermal Mass Multipliers				
Small Office	Miami	1980	1.98	4.99	10.00	14.94	19.91
Small Office	SF	1980	2.00	4.99	9.93	14.95	19.93
Small Office	Chicago	1980	2.01	4.99	9.98	14.96	19.95
Small Office	Fairbanks	1980	2.03	5.03	10.00	14.90	19.94
Small Office	Miami	2004	2.00	4.96	9.92	14.73	19.66
Small Office	SF	2004	1.90	4.98	9.46	14.81	19.87
Small Office	Chicago	2004	1.99	4.92	10.14	14.84	19.67
Small Office	Fairbanks	2004	2.02	4.96	9.93	14.78	19.75

Known very close to calculated ➔ check!

**Much closer than ASHRAE guidelines for calibration

Validation Results for Zone Infiltration

Building Vintage Location	Infiltration Inputs			Infiltration calculation results (NMBE)				
	Design flow rate input (ACH)	Schedule		CORE_ZN	PERIMETER_ZN_1	PERIMETER_ZN_2	PERIMETER_ZN_3	PERIMETER_ZN_4
Small Office Pre1980 5A:Chicago	1	Constant: 1		0.8%	1.1%	1.4%	1.2%	1.0%
	2			0.1%	0.1%	0.8%	0.1%	0.3%
	3			-1.4%	-1.2%	-0.7%	-1.4%	-1.4%
	1	Quarter schedule 6am - 10pm: 0.25		1.2%	1.8%	1.5%	1.8%	1.7%
	2			1.4%	2.0%	1.8%	1.9%	1.6%
	3			0.3%	0.6%	1.1%	0.9%	0.4%
	1	Quarter Gradient Sch		-0.9%	-1.0%	-0.9%	-1.0%	-1.2%
	2			-0.8%	-0.4%	0.1%	-0.8%	-0.8%
	3			-1.6%	-1.2%	-1.2%	-1.1%	-1.5%

Known very close to calculated ➔ check!

Validation II — Measured Data From FLEXLAB

What does this prove?

- Hybrid modeling works under real-world conditions

Use measured data from FLEXLAB facility

- Three levels of internal mass
- Four levels of infiltration rates
- Two-month experiment
- Use the calibrated EnergyPlus model
- Time-interval data from sensors (air flow, temperature), weather station, and meters

FLEXLAB Test Plan

Test period: April and May 2016

Test ID	Internal Mass Design	Infiltration Design	Estimated Period	Test Days
Setup	Experiment preparation, locate sensors, install and check fan for controlled outside air supply		4/4 Mon - 4/5 Tue	2
LM.0	Light (typical office setting)	0.16 ACH, as-built	4/6 Wed - 4/9 Sat	4
LM.1		1 ACH, constant	4/10 Sun - 4/13 Wed	4
LM.2		5 ACH, constant	4/14 Thr - 4/17 Sun	4
LM.3		1 - 5 ACH, scheduled	4/18 Mon - 4/21 Thr	4
HM.0	Heavy (with added books)	0.16 ACH, as-built	4/22 Fri - 4/25 Mon	4
HM.1		1 ACH, constant	4/26 Tue - 4/29 Fri	4
HM.2		5 ACH, constant	4/30 Sat - 5/3 Tue	4
HM.3		1 - 5 ACH, scheduled	5/4 Wed - 5/7 Sat	4
NM.0	No internal mass (empty space)	0.16 ACH, as-built	5/8 Sun - 5/11 Wed	4
NM.1		1 ACH, constant	5/12 Thr - 5/15 Sun	4
NM.2		5 ACH, constant	5/16 Mon - 5/19 Thr	4
NM.3		1 - 5 ACH, scheduled	5/20 Mon - 5/23 Mon	4

Measurement:
1. Zone free-floating air temperature
2. Outdoor air flow rate and temperature
3. Weather data

Infiltration design:
Use a variable speed fan to control air flow rate ranging from 1 to 5 ACH

Internal mass design:
Light office furniture,
Heavy mass with added books

Internal heat gain:
Use typical office settings

Progress and Accomplishments

Accomplishments:

- Developed the algorithms
- Implemented in a custom branch of EnergyPlus for testing and validation
- Validated simulated data
- Designed the FLEXLAB experiment

Market Impact:

- Estimated potential energy savings: 1.0 Quads
- Assumptions: 16.5 Quad of the current existing building market size, leading to an estimate of 20% increase of the potential 30% retrofit savings which is about 1.0 Quad ($16.5 \times 30\% \times 20\% = 1.0$)

Awards/Recognition:

- Project was mentioned in ConstructionPro NETWORK Magazine on 8/8/2014

Lessons Learned:

- Use the FLEXLAB calibrated model to minimize impact of uncertainty of parameters

Project Integration and Collaboration

Project Integration:

- Following EnergyPlus feature development, testing & release process
- Collaboration with FLEXLAB engineers to design & conduct experiment

Partners, Subcontractors, and Collaborators:

- Cost share from CEC PIER project: "Small and Medium Building Efficiency Toolkit and Community Demonstration Program"

Communications:

- Public webinar coming up

Publications:

- Two articles in preparation: Building Performance Simulation & Energy and Buildings

Next Steps and Future Plans

Next steps

- FLEXLAB empirical validation
- Fine tune the model
- Release in EnergyPlus V8.6 (September 2016)
- Outreach via a public webinar

Future plans

- Quantify calibration improvements
- Expose new functionality to users via OpenStudio

REFERENCE SLIDES

Project Plan and Schedule

Project Schedule								
Project Start: 10/1/2014		Completed Work						
Projected End: 9/30/2016		Acitive Task (in progress work)						
		Milestone/Deliverable (Originally planned)						
		Milestone/Deliverable (Actual)						
	FY2015				FY2016			
Task	Q1(Oct-Dec)	Q2(Jan-Mar)	Q3(Apr-Jun)	Q4(Jul-Sep)	Q1(Oct-Dec)	Q2(Jan-Mar)	Q3(Apr-Jun)	Q4(Jul-Sep)
Past Work								
Q1 Literature review								
Q2 Development of algorithms (Internal Mass)								
Q3 New feature proposal development for EnergyPlus (Internal mass)								
Q3 Implementation in custom EnergyPlus								
Q4 Validation of results from hybrid modeling								
Go/No-Go Decision Point								
Q5 Development of algorithms (Infiltration)								
Q6 Implementation and validation of the Infiltration								
Q6 Design of experiments in the FLEXlab testbed								
Q6 Development and calibration of EnergyPlus model for testbed								
Current / Future Work								
Q7 Conduct the experiment using FLEXLAB and validate the hybrid model								
Q7 Fine tune hybrid modeling algorithm								
Q8 Refine the new feature proposal								
Q8 Update and test code								
Q8 New feature check-in								
Q8 Technology-to-Market Strategy & Commercialization Plan								

Project Budget

Project Budget:

FY15: $300K

FY16: $300K

Variances: Not Applicable

Cost to Date:

FY15: 100%

FY16: 30%

Additional Funding: NA

Budget History					
Oct 2014 – FY 2015 (past)		FY 2016 (current)		FY 2017 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$300K	$33K	$300K	$33K	N/A	N/A

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