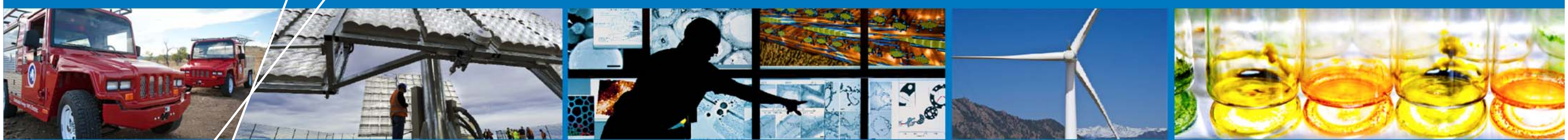
Evaluation of Automated Utility Bill Calibration Methods



BA Technical Update Meeting

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Utility Bill Calibration

- "Calibrate" or "true-up" building energy models to utility bill data to increase the accuracy of retrofit savings predictions
- Calibration methods typically involve adjusting input parameters
- Predict retrofit savings using the adjusted (calibrated) model

Background: BESTEST-EX

- **BESTEST-EX is a suite for testing calibration methods and retrofit savings predictions associated with audit software**
- **Field trials showed that:**
  - Retrofit savings predictions are generally improved by calibration
  - Utility bills can be matched for the wrong reasons
- **Provides a procedure for self-testing calibration methods**
  - Generate synthetic utility bill data with the tested program

Utility Bill Calibration

- **Methods vary:**
  - Manual
    - Depends on user experience
    - Lack of repeatability/transparency
  - Automated
    - Requires limited decision-making, but less flexible
    - Can be computationally expensive

Industry Standards

- **ANSI/BPI-2400-S-2012**
  - Utility bill requirements and weather normalization procedures
  - Detailed calibration acceptance criteria
  - Model input constraints
  - Input adjustments: "…may be done by the user, or by the software, respecting all required input constraints…"
    - How to optimally adjust inputs?
- **ANSI/RESNET Calibration Test Method**
  - Under development, led by NREL
  - To be used by software developers to test and improve calibration methods

Research Goals

- **Develop and implement automated calibration methods which improve accuracy and consistency of residential retrofit analysis**
  - Investigate tradeoffs between accuracy, computational cost, and repeatability
- **Explore impact of utility data frequency and sub-metering**

Technical Approach

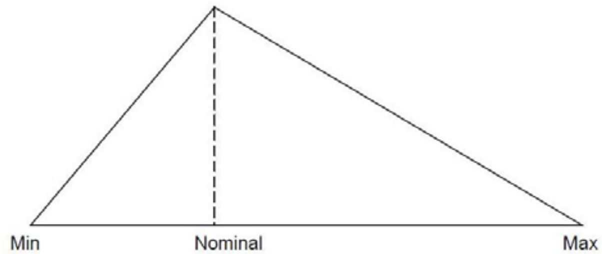
Technical Approach

- **Define a 1960's-era, all-electric house in Las Vegas, NV (BESTEST-based)**

Category	Pre-retrofit characteristics
Vented crawlspace	2.0 ACH, R-19 between joists
Exterior walls	2 x 4, 16" o.c., wood siding, R-1.01 air gap
Unfinished attic	2 x 6 joists, R-11 insulation
Window type	Single pane, aluminum frame, U = 0.774, SHGC = 0.679
Window distribution	20% of exterior wall, 33% on N/S, 17% on E/W
Air conditioner	SEER 10
Furnace	Electric
Uninsulated ducts	In crawlspace, leakage fraction = 0.30
Living space SLA	0.000886
Water heater	Electric, energy factor = 0.92
Thermostat setpoints	Heating 68°F, cooling 78°F

Technical Approach

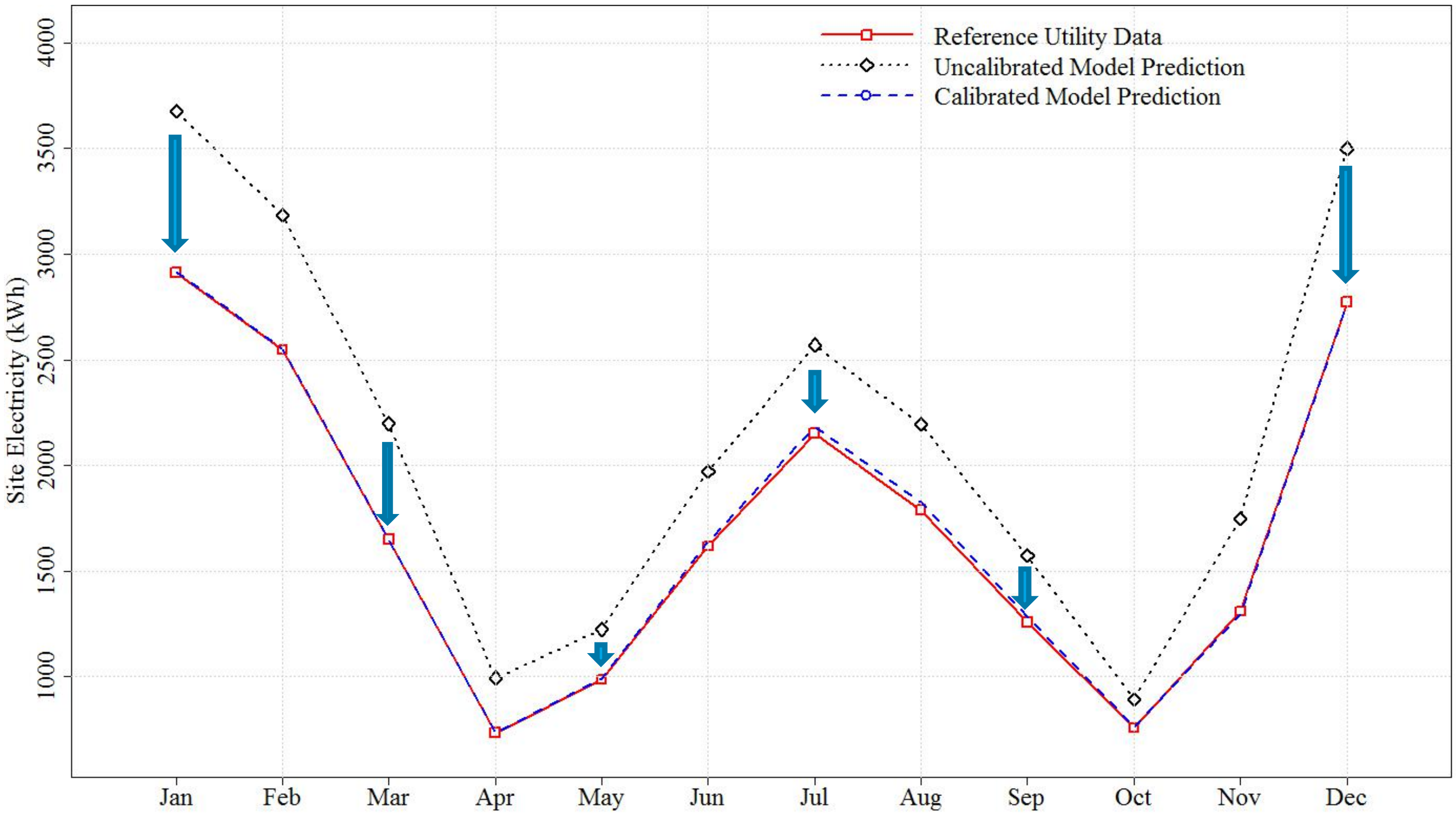
- **Assign uncertainty ranges to inputs**



- **Randomly select explicit input values from ranges: <u>reference model</u>**
- **Simulate model: <u>synthetic reference utility bill data</u>**
  - Two scenarios: over-prediction, under-prediction
  - Data frequencies: monthly, hourly

Technical Approach

- **Auto-calibrate models to reference utility bill data**



Technical Approach

- **Run reference, uncalibrated, and calibrated models thru retrofit scenarios**
  - Air-Seal
  - Attic Insulation
  - Wall Insulation
  - Programmable Thermostat
  - Low-e Windows
  - Duct Sealing and Insulation
  - AC Replacement
  - Combined

Technical Approach

- **Calculate savings: REF, UNCAL, CAL**
- **Calculate Benefit of Calibration (*BoC*) for each retrofit scenario**

$$BoC = \left|UNCAL - REF\right| - \left|CAL - REF\right|$$

- **Compare *BoC* values across:**
  - o Calibration methods
  - o Over- and under-prediction
  - o Utility data frequencies

Calibration Methods

Calibration Methods

- **ASHRAE 1051 Research Project (Reddy *et al*, 2006)**
  - Suggests using a consistent and systematic calibration methodology
  - Needs to be adapted for residential applications
- **Adapted components of ASHRAE 1051-RP**
  - Identified most influential model input parameters
  - Adjusted these parameters during calibration

Calibration Methods

- **Adapted and implemented three auto-calibration methods using:**
  - o Python scripting
  - o BEopt software (with DOE-2.2 simulation engine)
  - o Simulated annealing optimization algorithm

$$h'_j = h_j + v_j \Delta h_j \sigma^3_{n,j}$$

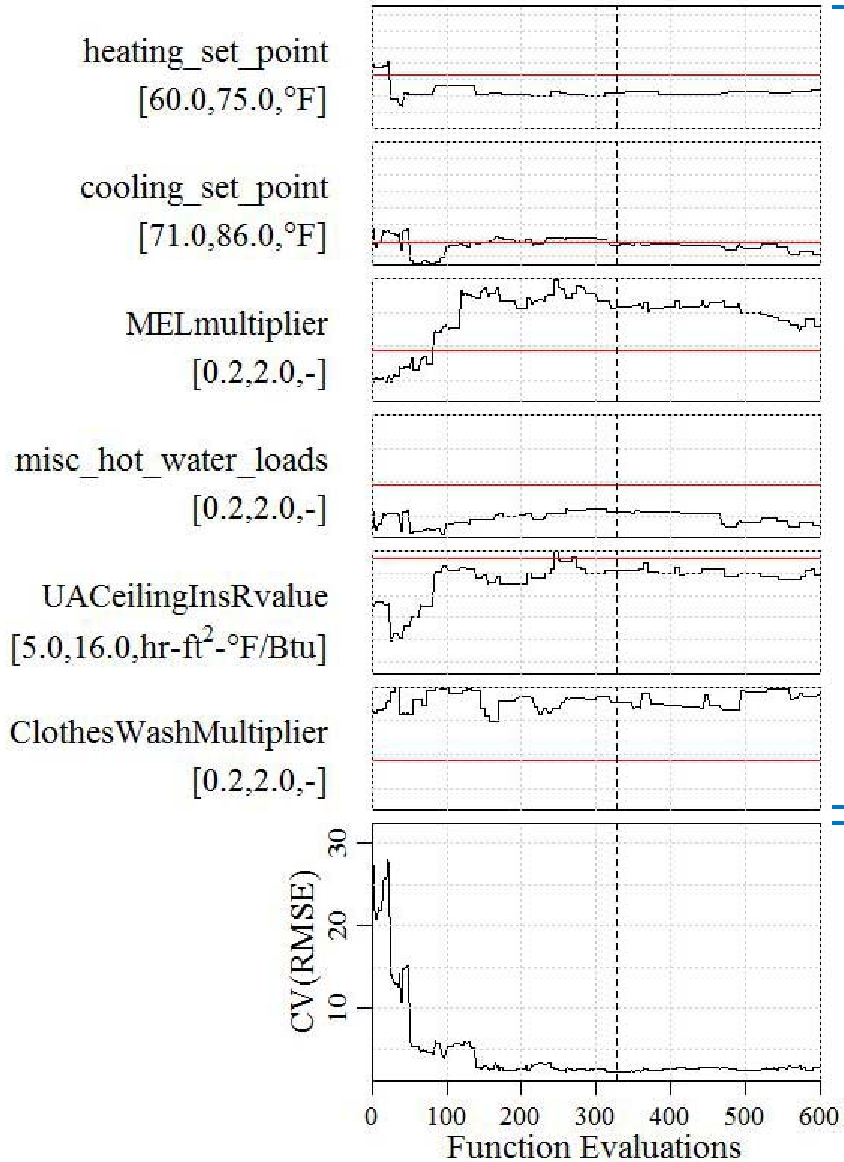
Calibration Methods

- **Simulated annealing optimization steps:**
  1. Adjust the 6 most influential model parameters
  2. Predict energy use for the adjusted model
  3. Compare predicted energy use to billing data
  4. Repeat steps 1 – 3 for 100 iterations
  5. Model corresponding to best agreement is calibrated model

Calibration Methods

- **Simulated annealing optimization**
  - Advantages
    - Thorough
    - Ability to jump from local minima
  - Disadvantages
    - Costly if annual simulations are used

Calibration Methods



Parameter convergence

Residual convergence

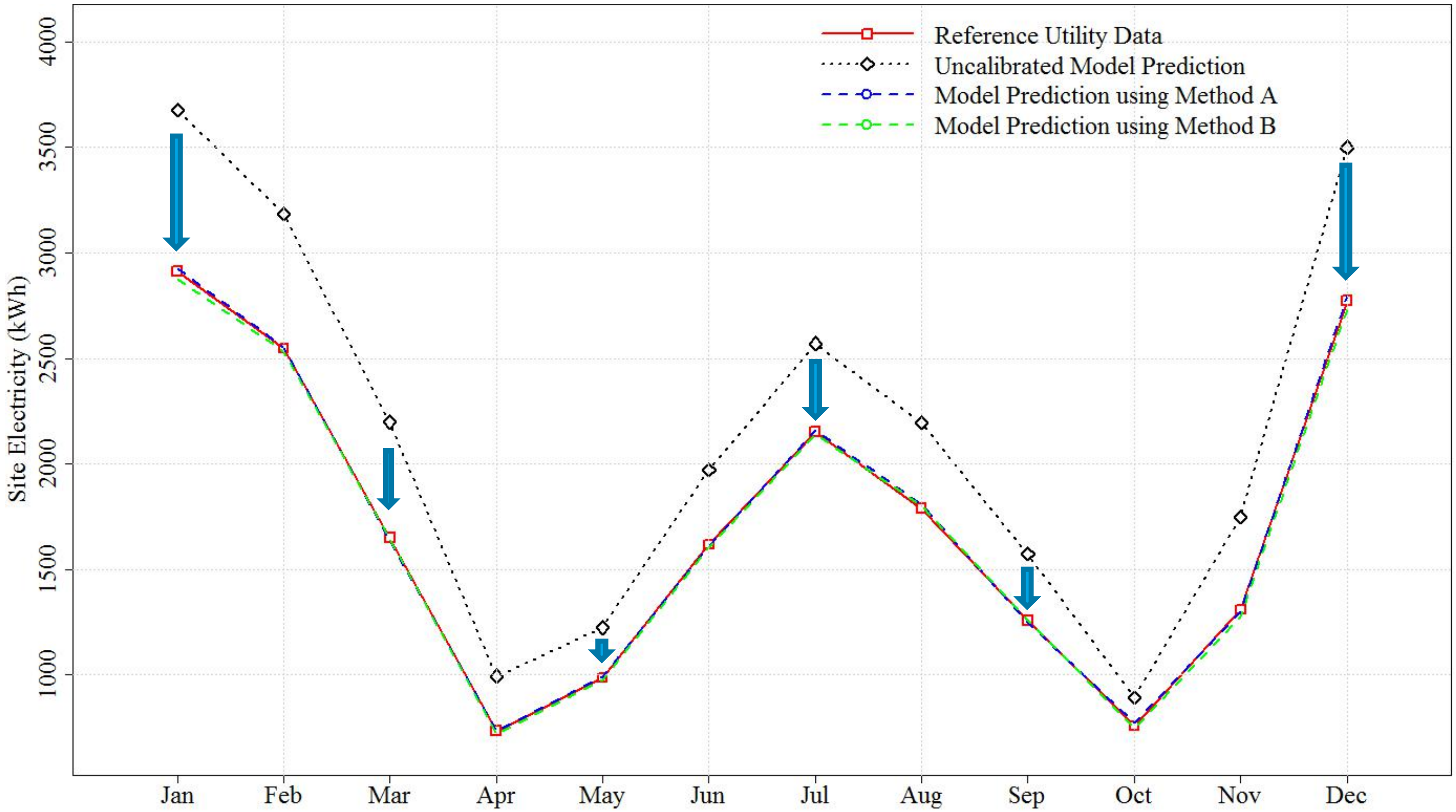
Calibration Methods

	Method A (ASHRAE 1051-RP-based)	**Method B**	**Method C**
Number of calibrated model solutions (optimizations)	10; used to predict ranges of energy savings	1	1
Tool used to predict energy use	BEopt/DOE-2.2	BEopt/DOE-2.2	Statistical models (based on a set of BEopt/DOE-2.2 simulations and results)
Computational cost	Highest	Mid	Lowest

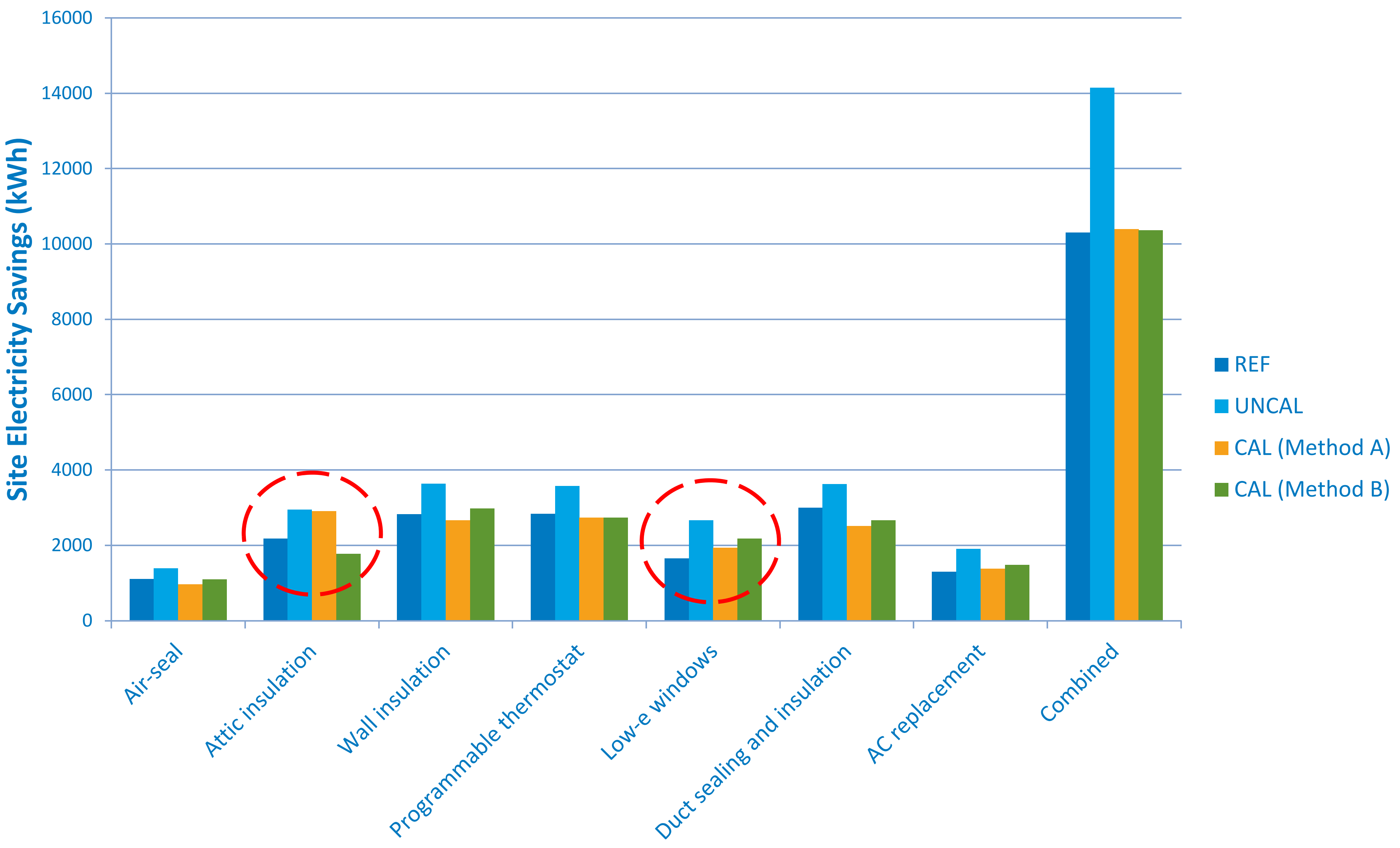
3 Results, 3 Key Takeaways

Result 1, Goodness-of-Fit

- **Good agreement with reference utility bill data using both Methods A and B (e.g.)**



Result 1, Goodness-of-Fit



Key Takeaway 1, Goodness-of-Fit

- Goodness-of-fit does not guarantee a good calibration (under-determined problem)
- Need smart calibration methods that optimize accuracy
- Must look at savings predictions when testing calibration methods

Result 2, Benefit of Calibration

$$BoC = |UNCAL - REF| - |CAL - REF|$$

- ***TBoC*** **is the sum of** ***BoC*** **across retrofits**

Over-prediction	***TBoC***	
	Monthly	Hourly
Method A	7196.4	7445.0
Method B	6627.2	7179.6
Method C	6909.1	7172.0
Under-prediction	***TBoC***	
	Monthly	Hourly
Method A	-471.7	2183.0
Method B	315.0	2030.7
Method C	104.4	1117.8

Key Takeaway 2, Benefit of Calibration

- Accuracy of Method C was comparable to Methods A and B (the more expensive methods)
- Generally, calibrations to higher-frequency data produced more accurate energy savings predictions

Result 3, Computational Cost

Method	Component	Total annual simulations	Minimum series
A	Sensitivity analysis Central composite design Simulated annealing Retrofits **Total**	2500 N/A 6360 80 **8940**	1 N/A 602 1 **604**
B	Sensitivity analysis Central composite design Simulated annealing Retrofits **Total**	2400 N/A 951 8 **3359**	1 N/A 602 1 **604**
C	Sensitivity analysis Central composite design Simulated annealing Retrofits **Total**	2400 77 0 8 **2485**	1 1 0 1 **3**

Key Takeaway 3, Computational Cost

- Simulations within each component of Method C may be parallelized such that the entire calibration method equates to only three annual simulations in series
- Low-cost potential of using statistical models during optimization make this a tractable calibration option in the residential sector

Summary/Recommendations

- **It is feasible to implement automated methods for residential building model calibration:**
  - Supports repeatability across users
  - Encourages transparency
- **Even with automated method, don't assume that good fit to utility bills means you have a good calibration; test it! (e.g., using SMOT)**
- **Design calibration methods to take advantage of parallel-computing to reduce computational cost (e.g., statistical model)**
- **Take advantage of higher-frequency utility bill data when present (contains additional informational content for home performance)**

Uncertainty ranges

Table A.1: Operational Inputs and Uncertainty Ranges

Approximate input[1]	Minimum	Nominal	Maximum	Units
AnnualExteriorLightingEnergy	45.0	179.0	446.0	kWh/yr
AnnualInteriorLightingEnergy	234.0	935.0	2336.0	kWh/yr
cooling_set_point	71.0	78.0	86.0	°F
ClothesWashMultiplier[2]	0.2	0.8	2.0	-
FractionWindowAreaOpen	0.000	0.133	0.467	frac
FurnitureAreaFraction	0.3	0.4	0.5	frac
FurnitureConductivity	0.5603	0.8004	1.0405	Btu·in/hr·ft^2·°F
FurnitureSolarAbsorptance	0.4	0.6	0.8	frac
FurnitureSpecHeat	0.261	0.290	0.319	Btu/lb·°F
FurnitureWeight	2.0	8.0	14.0	lb/ft^2
heating_set_point	60.0	68.0	75.0	°F
interior_shading	0.5	0.6	1.0	frac
KitchenAppliancesMultiplier[3]	0.2	0.8	2.0	-
misc_hot_water_loads	0.2	0.8	2.0	-
MELmultiplier	0.2	0.8	2.0	-
MGLmultiplier	0.2	0.8	2.0	-
RangeHoodExhaust	80.0	100.0	120.0	cfm
RefrigeratorAnnualEnergy	303.8	434.0	564.2	kWh/yr
WaterHeaterSetpoint	110.0	125.0	140.0	°F

[1] Bolded inputs are influential inputs.

[2] Values selected from this range are used for the following BEopt™ inputs: CWBABMultiplierElec, CWBABMultiplierHotWater, DryerBABMultiplierElec.

[3] Values selected from this range are used for the following BEopt™ inputs: DWBABMultiplierElec, DWBABMultiplierHotWater, CookingRangeBABMultiplierElec.

Uncertainty ranges

Table A.2: Asset Inputs and Uncertainty Ranges

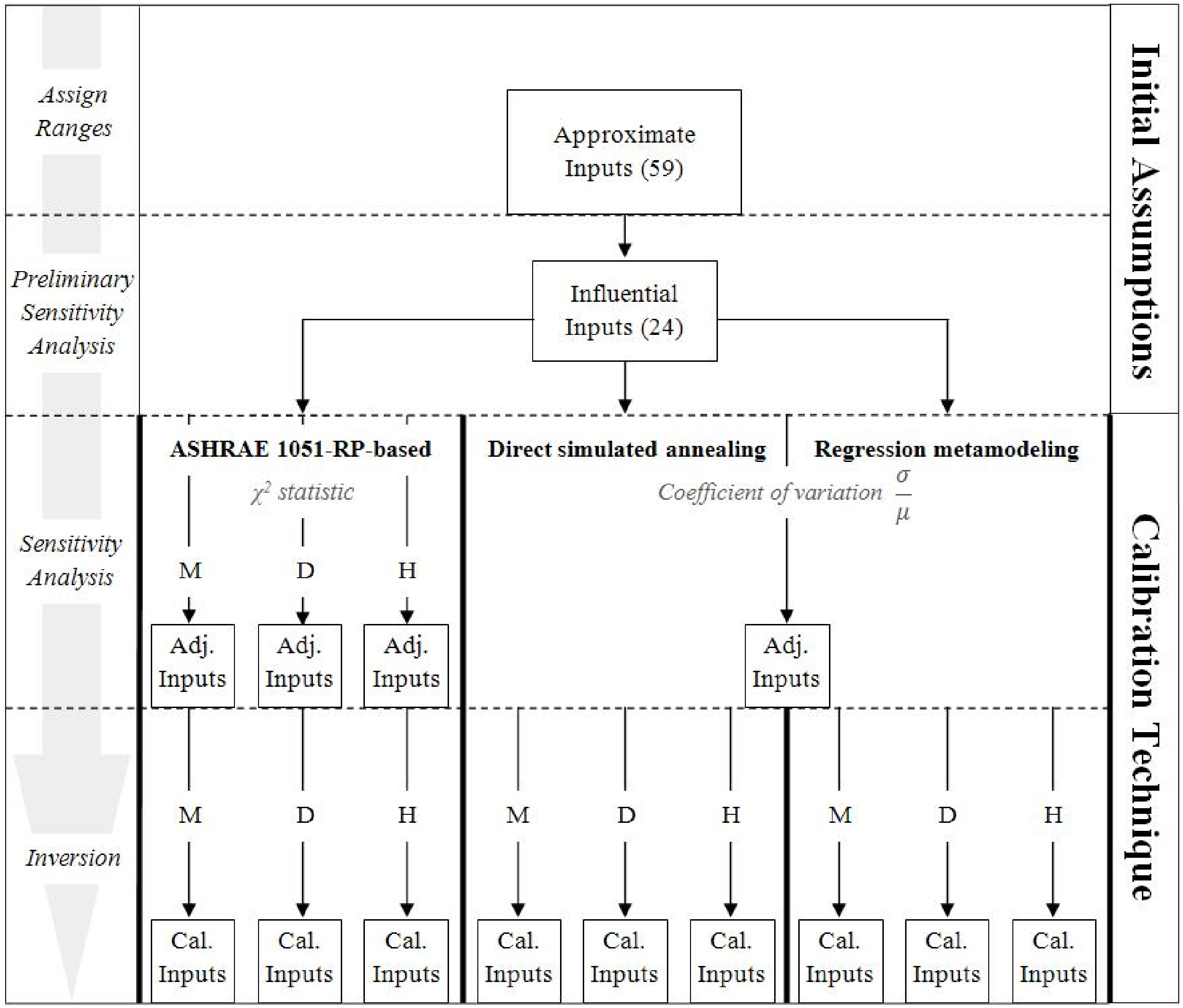
Approximate input[1]	Minimum	Nominal	Maximum	Units
AC_CoolingSEER	9.0	10.0	10.5	kBtu/kWh
CarpetPadRValue	1.456	2.080	2.704	hr·ft^2·°F/Btu
CavityDepth1	3.325	3.500	3.675	in
CavityInsRvalue1	0.80	1.01	1.80	hr·ft^2·°F/Btu
CrawlACH	1.0	2.0	4.0	air changes/hr
CrawlCeilingFramingFactor	0.08	0.10	0.12	frac
CrawlCeilingRcavity	13.3	19.0	24.7	hr·ft^2·°F/Btu
DuctLeakage[2]	0.24	0.30	0.36	frac of AH fan flow
FinishAbsorptivity	0.5	0.6	0.8	frac
FinishConductivity	0.4570	0.6528	0.8486	Btu·in/hr·ft^2·°F
FinishDensity	36.0	40.0	44.0	lb/ft^3
FinishEmissivity	0.87	0.90	0.93	frac
FinishSpecificHeat	0.252	0.280	0.308	Btu/lb·°F
FinishThickness	0.418	0.440	0.462	in
FramingFactor1	0.20	0.25	0.30	frac
GypsumThicknessCeiling	0.4754	0.5004	0.5254	in
GypsumThicknessExtWall	0.4754	0.5004	0.5254	in
gypsum_conductivity	0.7778	1.1112	1.4446	Btu·in/hr·ft^2·°F
gypsum_density	45.0	50.0	55.0	lb/ft^3
gypsum_specific_heat	0.234	0.260	0.286	Btu/lb·°F
LivingSpaceSLA	0.000619	0.000886	0.000974	in^2/ft^2
PartitionWallMassConductivity	0.7778	1.1112	1.4446	Btu·in/hr·ft^2·°F
PartitionWallMassDensity	45.0	50.0	55.0	lb/ft^3
PartitionWallMassFractionOfFloorArea	1.064	1.330	1.596	frac
PartitionWallMassSpecificHeat	0.234	0.260	0.286	Btu/lb·°F
PartitionWallMassThickness	0.4754	0.5004	0.5254	in
RoofingMaterialAbsorptivity	0.5	0.6	0.8	frac
RoofingMaterialEmissivity	0.87	0.90	0.93	frac
ShelterCoefficient	0.4	0.5	0.7	frac
UACeilingFramingFactor	0.08	0.10	0.12	frac
UACeilingInsRvalue[3]	5.0	11.0	16.0	hr·ft^2·°F/Btu
UARoofFramingFactor	0.08	0.10	0.12	frac
UARoofFramingThickness	5.225	5.500	5.775	in
UnfinishedAtticSLA	0.00167	0.00333	0.00667	in^2/ft^2
WaterHeaterEnergyFactor	0.86	0.92	0.93	frac
WindowSHGC	0.645	0.679	0.713	coefficient
WindowUvalue	0.619	0.774	0.833	Btu/hr·ft^2·°F
wood_conductivity	0.5603	0.8004	1.0405	Btu·in/hr·ft^2·°F
wood_density	28.8	32.0	35.2	lb/ft^3
wood_specific_heat	0.261	0.290	0.319	Btu/lb·°F

[1] Bolded inputs are influential inputs.

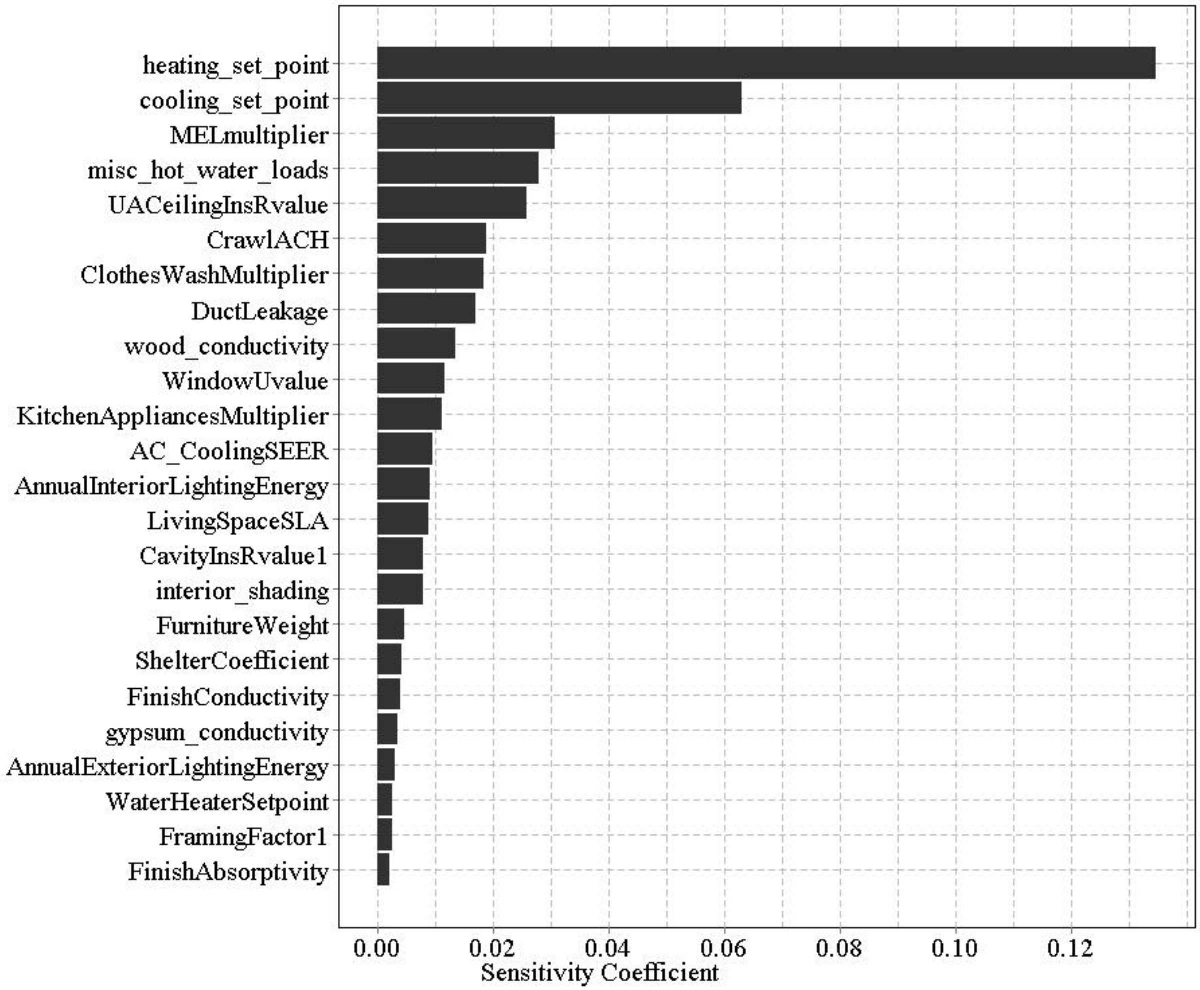
[2] Values selected for this range are implemented by proportionally scaling the following BEopt^{TM} inputs: AHLeakSA, AHLeakRA, ReturnLeak, SupplyLeak.

[3] After the value was selected from this range, the nominal insulation conductivity value was used to calculate the value of UACeilingJoistThickness, which was then also used for the value of UACeilingInsThickness.

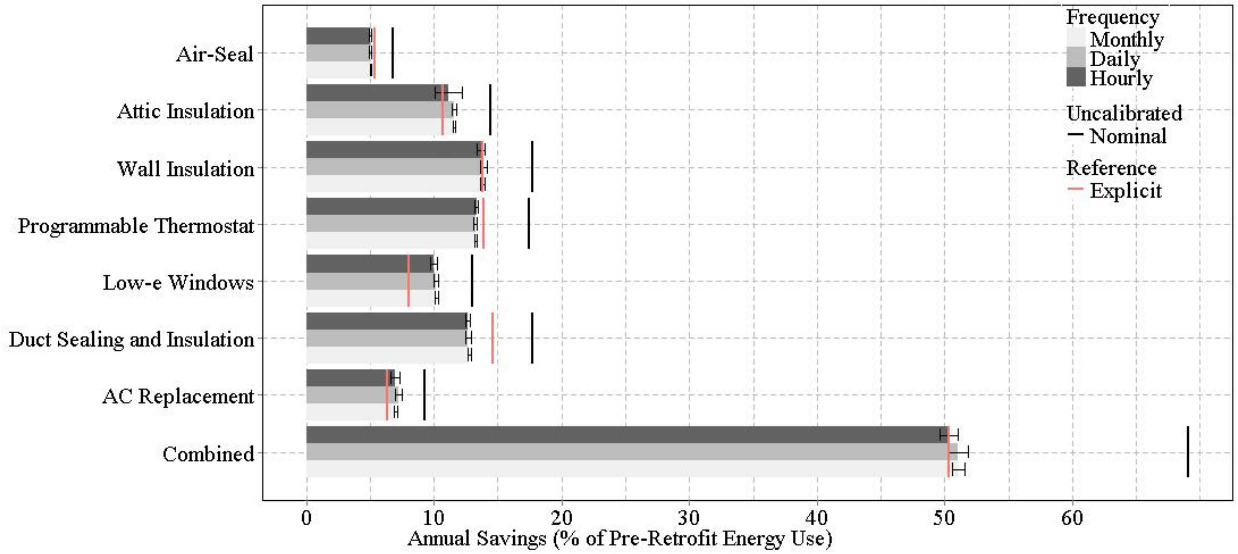
Flowchart

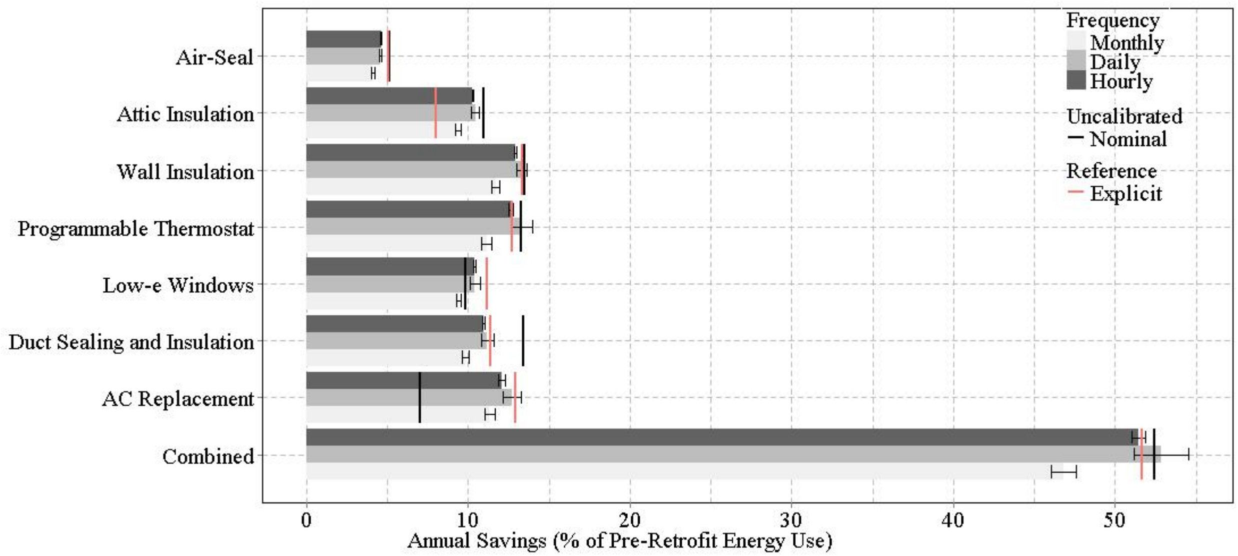

Assign Ranges
Preliminary Sensitivity Analysis
Sensitivity Analysis
Inversion
Approximate Inputs (59)
Influential Inputs (24)
ASHRAE 1051-RP-based
Direct simulated annealing
Regression metamodeling
χ^2 statistic
Coefficient of variation $\frac{\sigma}{\mu}$
M
D
H
Adj. Inputs
Cal. Inputs
Initial Assumptions
Calibration Technique

Sensitivity analysis

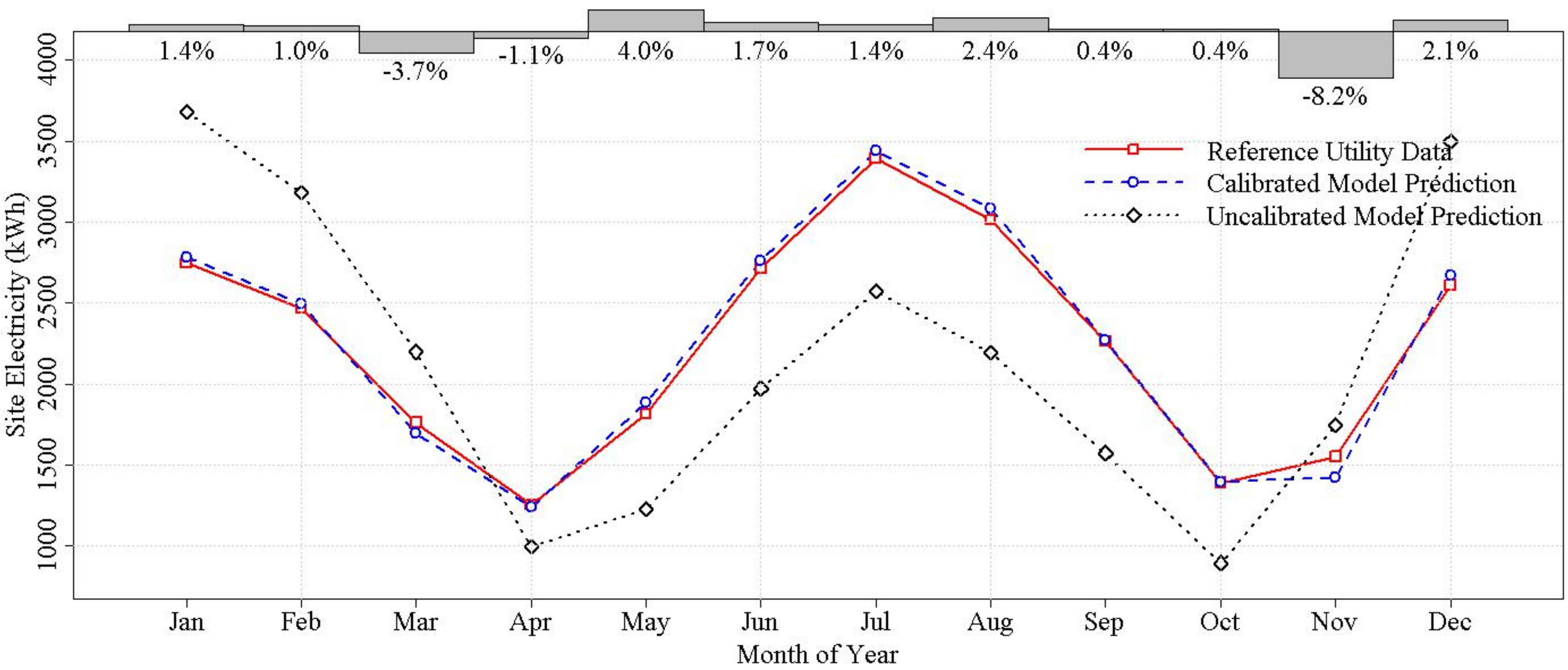


ASHRAE 1051-RP





Under-prediction



Explicit values, over-prediction

Table A.3: Reference Model Input Values for Scenario 1

Approximate input	ν_i	Approximate input	ν_i
AC_CoolingSEER	10.12	heating_set_point	65.47
AnnualInteriorLightingEnergy	574.46	interior_shading	0.74
AnnualExteriorLightingEnergy	270.57	KitchenAppliancesMultiplier	1.20
CarpetPadRValue	2.01	LivingSpaceSLA	0.00085
CavityDepth1	3.51	MELmultiplier	0.55
CavityInsRvalue1	1.37	MGLmultiplier	0.95
ClothesWashMultiplier	0.64	misc_hot_water_loads	0.87
cooling_set_point	82.01	PartitionWallMassConductivity	0.94
CrawlACH	3.05	PartitionWallMassDensity	49.18
CrawlCeilingFramingFactor	0.11	PartitionWallMassFractionOfFloorArea	1.36
CrawlCeilingRcavity	21.81	PartitionWallMassSpecificHeat	0.26
DuctLeakage	0.31	PartitionWallMassThickness	0.49
FinishAbsorptivity	0.57	RangeHoodExhaust	110.49
FinishConductivity	0.63	RefrigeratorAnnualEnergy	480.27
FinishDensity	40.85	RoofingMaterialAbsorptivity	0.56
FinishEmissivity	0.90	RoofingMaterialEmissivity	0.91
FinishSpecificHeat	0.27	ShelterCoefficient	0.47
FinishThickness	0.43	UACeilingFramingFactor	0.10
FractionWindowAreaOpen	0.16	UACeilingInsRvalue	12.90
FramingFactor1	0.24	UARoofFramingFactor	0.11
FurnitureAreaFraction	0.38	UARoofFramingThickness	5.56
FurnitureConductivity	0.93	UnfinishedAtticSLA	0.0031
FurnitureSolarAbsorptance	0.61	WaterHeaterEnergyFactor	0.87
FurnitureSpecHeat	0.27	WaterHeaterSetpoint	138.37
FurnitureWeight	8.20	WindowSHGC	0.66
GypsumThicknessCeiling	0.49	WindowUvalue	0.70
GypsumThicknessExtWall	0.49	wood_conductivity	0.79
gypsum_conductivity	1.29	wood_specific_heat	0.29
gypsum_specific_heat	0.26	wood_density	29.58
gypsum_density	45.73		

Explicit values, under-prediction

Table A.4: Reference Model Input Values for Scenario 2

Approximate input	ν_i	Approximate input	ν_i
AC_CoolingSEER	9.70	heating_set_point	66.65
AnnualInteriorLightingEnergy	1703.27	interior_shading	0.88
AnnualExteriorLightingEnergy	272.04	KitchenAppliancesMultiplier	0.73
CarpetPadRValue	2.19	LivingSpaceSLA	0.00079
CavityDepth1	3.42	MELmultiplier	0.93
CavityInsRvalue1	0.99	MGLmultiplier	1.00
ClothesWashMultiplier	0.92	misc_hot_water_loads	0.96
cooling_set_point	73.69	PartitionWallMassConductivity	1.19
CrawlACH	2.74	PartitionWallMassDensity	53.03
CrawlCeilingFramingFactor	0.10	PartitionWallMassFractionOfFloorArea	1.30
CrawlCeilingRcavity	19.69	PartitionWallMassSpecificHeat	0.25
DuctLeakage	0.29	PartitionWallMassThickness	0.49
FinishAbsorptivity	0.74	RangeHoodExhaust	103.64
FinishConductivity	0.63	RefrigeratorAnnualEnergy	494.23
FinishDensity	39.64	RoofingMaterialAbsorptivity	0.71
FinishEmissivity	0.93	RoofingMaterialEmissivity	0.92
FinishSpecificHeat	0.27	ShelterCoefficient	0.52
FinishThickness	0.44	UACeilingFramingFactor	0.098
FractionWindowAreaOpen	0.19	UACeilingInsRvalue	15.25
FramingFactor1	0.26	UARoofFramingFactor	0.09
FurnitureAreaFraction	0.43	UARoofFramingThickness	5.69
FurnitureConductivity	0.65	UnfinishedAtticSLA	0.0031
FurnitureSolarAbsorptance	0.71	WaterHeaterEnergyFactor	0.89
FurnitureSpecHeat	0.30	WaterHeaterSetpoint	122.91
FurnitureWeight	7.11	WindowSHGC	0.69
GypsumThicknessCeiling	0.51	WindowUvalue	0.76
GypsumThicknessExtWall	0.51	wood_conductivity	0.68
gypsum_conductivity	1.24	wood_specific_heat	0.28
gypsum_specific_heat	0.28	wood_density	31.01
gypsum_density	53.15		

Central composite design

$$
\mathbf{X} = \begin{array}{c|cccc|ccc|ccc}
\text{Intercept} & & \text{Design} & & & & \text{Interaction} & & & \text{Squared} & \\
1 & -\alpha & -\alpha & \cdots & -\alpha & (-\alpha)(-\alpha) & \cdots & (-\alpha)(-\alpha) & (-\alpha)(-\alpha) & \cdots & (-\alpha)(-\alpha) \\
1 & \alpha & -\alpha & \cdots & -\alpha & (\alpha)(-\alpha) & \cdots & (-\alpha)(-\alpha) & (\alpha)(\alpha) & \cdots & (-\alpha)(-\alpha) \\
 & & & \ddots & & & \ddots & & & \ddots & \\
1 & -\alpha & \alpha & \cdots & \alpha & (-\alpha)(\alpha) & \cdots & (\alpha)(\alpha) & (-\alpha)(-\alpha) & \cdots & (\alpha)(\alpha) \\
1 & \alpha & \alpha & \cdots & \alpha & (\alpha)(\alpha) & \cdots & (\alpha)(\alpha) & (\alpha)(\alpha) & \cdots & (\alpha)(\alpha) \\
1 & -1 & 0 & \cdots & 0 & 0 & \cdots & 0 & (-1)(-1) & \cdots & 0 \\
1 & 1 & 0 & \cdots & 0 & 0 & \cdots & 0 & (1)(1) & \cdots & 0 \\
1 & 0 & -1 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\
1 & 0 & 1 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 \\
 & & & \ddots & & & \ddots & & & \ddots & \\
1 & 0 & 0 & \cdots & 0 & 0 & \cdots & 0 & 0 & \cdots & 0
\end{array}
$$

$$\alpha = 2^{-\frac{\tau}{4}}$$