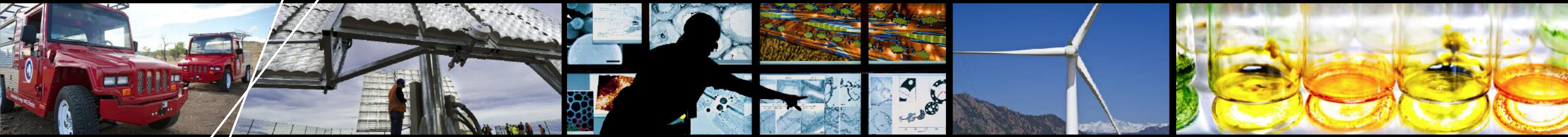
Calibration example with OpenStudio



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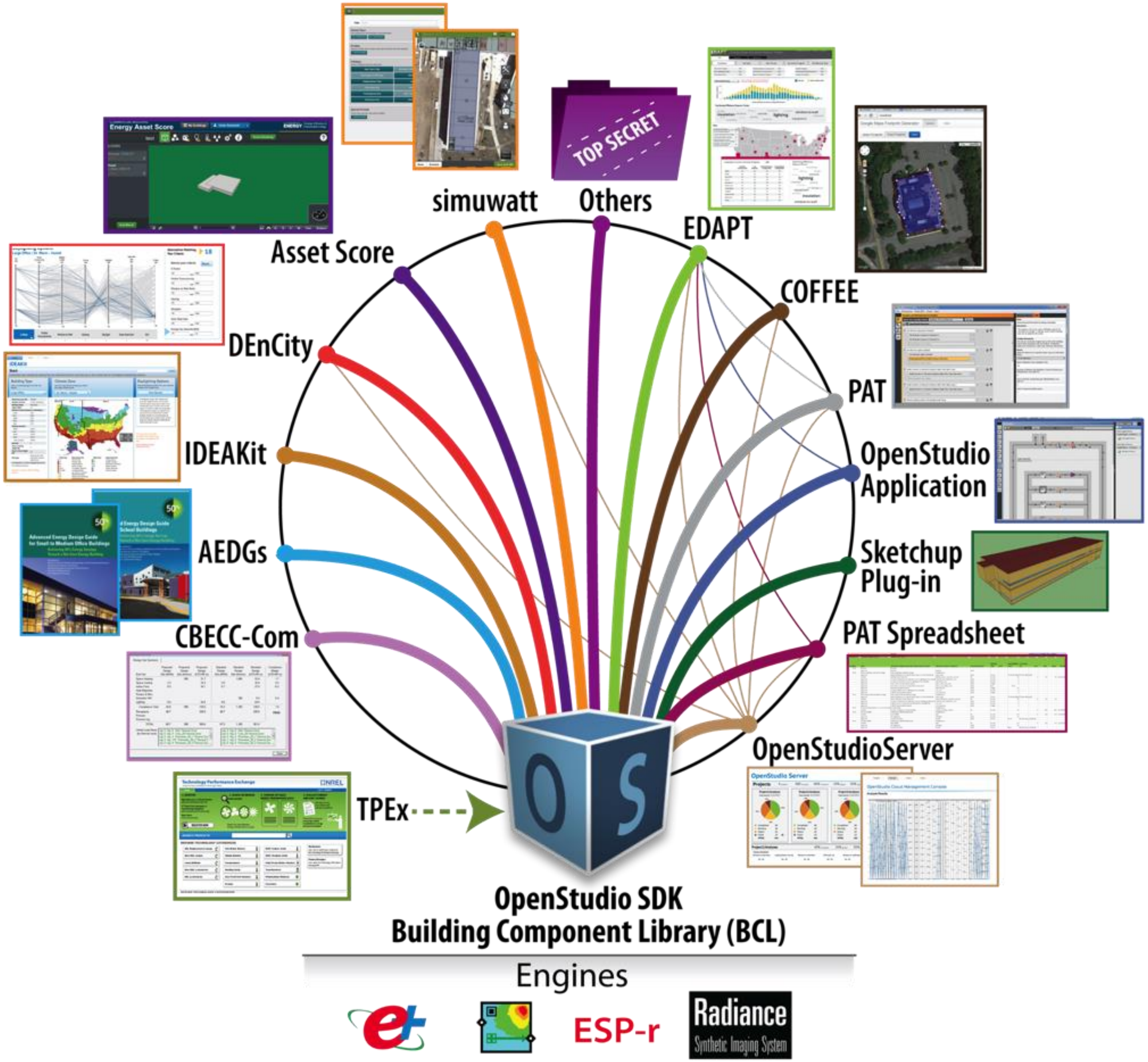
DOE'S Energy Modeling Ecosystem

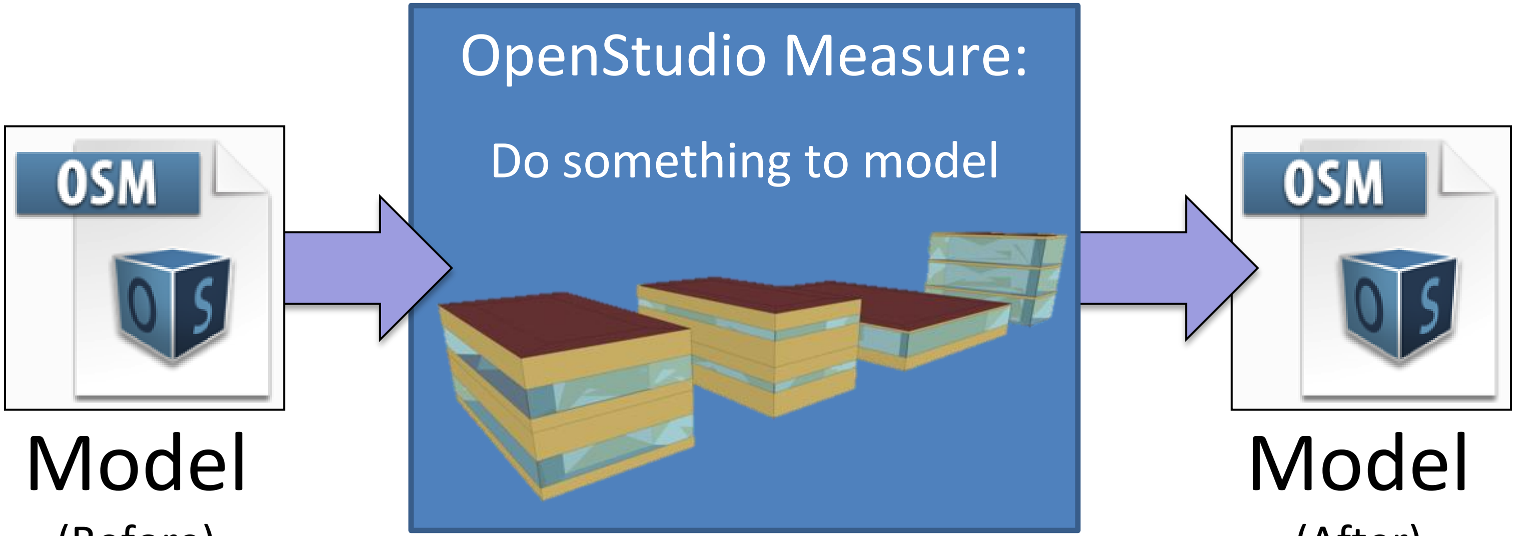
OpenStudio is an open source platform that bridges the gap between capable but complex engines and the easy-to-use applications that drive energy savings.

The Technology Performance Exchange (TPEx) and Building Component Library (BCL) provide raw data that powers the ecosystem.



OpenStudio Measures

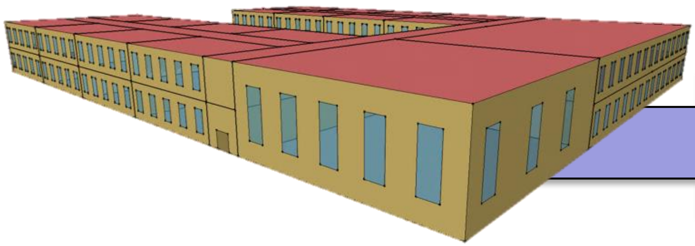
OpenStudio Measures are small scripts that transform building models **quickly** and **easily**



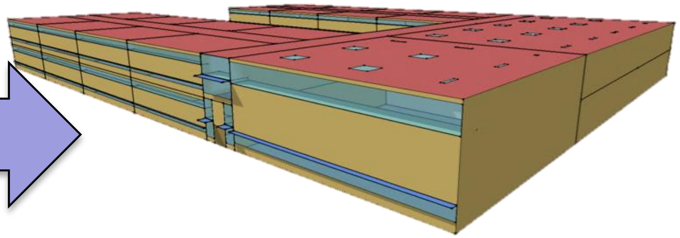
Model (Before)

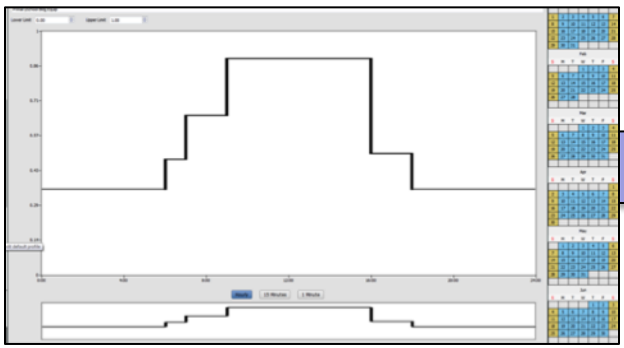
Model (After)

Sample Measures

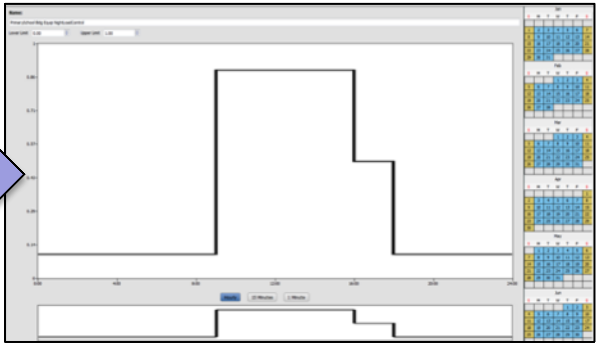


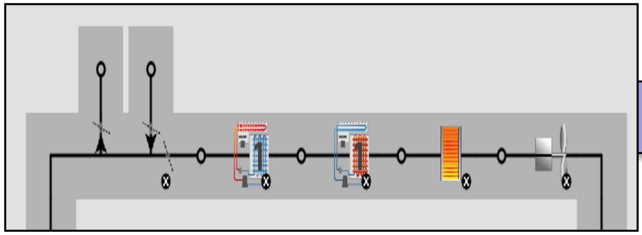
Daylighting Measure



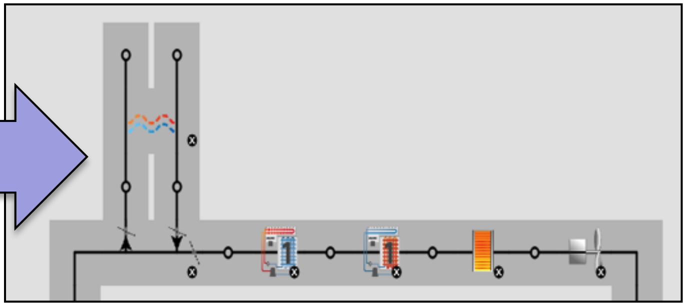


Night Setback Measure

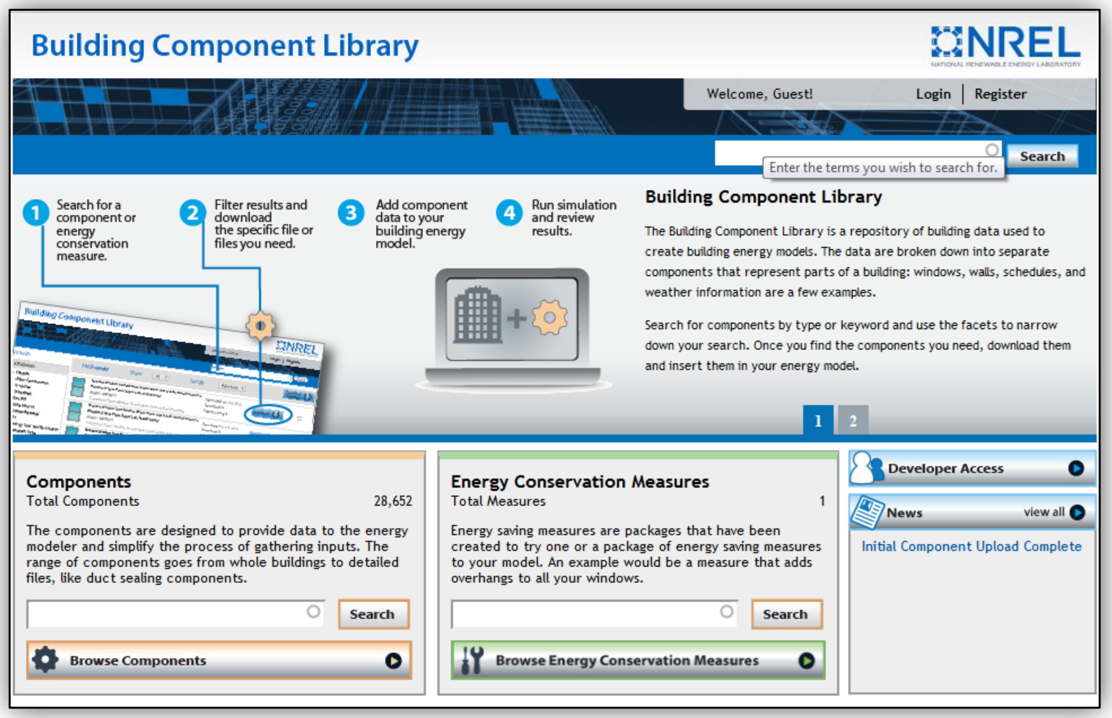




Add Heat Recovery Measure



The Building Component Library



- An Internet-connected source of building energy modeling data:
  - Enables drag-and-drop modeling for **quick** technology evaluation
  - Provides **consistent**, detailed inputs to drive decision-making
  - **Searchable** readily available within applications
  - The BCL is key to OpenStudio’s **extensibility**

Setting Up An Analysis: using the spreadsheet

This is the “Improve Fan Belt Efficiency” Measure

1		Inputs			Continuous Variable Description					Discrete Variable Description		
2	*Measure Display Name*	*Measure Class Name*										
3	*type*	*Parameter Display Name (will make machine name)*	*Variable Type*	*Static/Default Value*	*Min*	*Max*	*Mean*	*Std Dev*	*Delta X*	*Discrete Values*	*Discrete Weights*	*Distribution*
29	Reduce Electric Equipment Loads by	ReduceElectricEquipmentLoadsByPercentage										
30	argument	Apply the Measure to a Specific Space Type o	Choice	*Entire Building*								
31	variable	Electric Equipment Power Reduction	Double	0	-80	80	0	26.667	1			uniform_uncertain
39	Set Gas Burner Efficiency	SetGasBurnerEfficiency										
40	argument	Choose an Air Loop with a two speed DX Cool	Choice	*All Air Loops*								
41	variable	Burner Efficiency (fractional)	Double	0.8	0.78	0.98	0.8	0.0333	1			uniform_uncertain
50	Set COP for Single Speed DX Cooling	SetCOPforSingleSpeedDXCoolingUnits										
51	argument	Choose an Air Loop with a single speed DX Cc	Choice	*All Air Loops*								
52	variable	Rated COP	Double	4	2	5	4	0.5	0.25			uniform_uncertain
61	Change Electric Baseboard	ChangeElectricBaseboard										
62	argument	Baseboard Efficiency %	Double	1	0.9	1	0.95	0.0167	0.1			uniform_uncertain
63	variable	Baseboard Nominal Capacity (W)	Double	1450	0	3000	1450	500	10			uniform_uncertain
64	Improve Fan Belt Efficiency	ImproveFanBeltEfficiency										
65	argument	Choose an Air Loop to Alter.	Choice	*All Air Loops*								
66	variable	Motor Efficiency Change(%).	Double	0	-20	14	0	5.6667	1			uniform_uncertain
67	variable	Fan Efficiency Change(%).	Double	0	-20	30	0	8.3333	1			uniform_uncertain
68	argument	Remove Baseline Costs From Effected Cooling	Bool	FALSE								
69	argument	Increase in Material and Installation Cost for	Double	0								
70	argument	Increase in Demolition Costs for Electric Equip	Double	0								
71	argument	Years Until Costs Start	Integer	0								
72	argument	Demolition Costs Occur During Initial Constru	Bool	FALSE								
73	argument	Expected Life	Integer	15								
74	argument	Increase O & M Costs for Electric Equipment	Double	0								
75	argument	O & M Frequency	Integer	1								
76	Calibration Reports	CalibrationReports										
77	Adjust Thermostat Setpoints by Deg	AdjustThermostatSetpointsByDegrees										

Instructions | Setup | Variables | Outputs | BCL Measure Data | Lookups

- This measure has eleven possible inputs
- In this analysis we let two vary
- The other nine are held to default values

Setting Up An Analysis

This is where we specify default values and distributions

1		Inputs			Continuous Variable Description					Discrete Variable Description		
2	*Measure Display Name*	*Measure Class Name*										
3	*type*	*Parameter Display Name (will make machine name)*	*Variable Type*	*Static/Default Value*	*Min*	*Max*	*Mean*	*Std Dev*	*Delta X*	*Discrete Values*	*Discrete Weights*	*Distribution*
29	Reduce Electric Equipment Loads by	ReduceElectricEquipmentLoadsByPercentage										
30	argument	Apply the Measure to a Specific Space Type o	Choice	*Entire Building*								
31	variable	Electric Equipment Power Reduction	Double	0	-80	80	0	26.667	1			uniform_uncertain
39	Set Gas Burner Efficiency	SetGasBurnerEfficiency										
40	argument	Choose an Air Loop with a two speed DX Cool	Choice	*All Air Loops*								
41	variable	Burner Efficiency (fractional)	Double	0.8	0.78	0.98	0.8	0.0333	1			uniform_uncertain
50	Set COP for Single Speed DX Cooling	SetCOPforSingleSpeedDXCoolingUnits										
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52	variable	Rated COP	Double	4	2	5	4	0.5	0.25			uniform_uncertain
61	Change Electric Baseboard	ChangeElectricBaseboard										
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68	argument	Remove Baseline Costs From Effected Cooling	Bool	FALSE								
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71	argument	Years Until Costs Start	Integer	0								
72	argument	Demolition Costs Occur During Initial Constru	Bool	FALSE								
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74	argument	Increase O & M Costs for Electric Equipment	Double	0								
75	argument	O & M Frequency	Integer	1								
76	Calibration Reports	CalibrationReports										
77	Adjust Thermostat Setpoints by Deg	AdjustThermostatSetpointsByDegrees										

Instructions | Setup | Variables | Outputs | BCL Measure Data | Lookups

- The Fan Efficiency will change from -20% to 30% uniformly
- There’s LOTS of flexibility to add measures and vary their inputs

Setting Up and Running an Analysis

- **Other tabs in the spreadsheet let you:**
  - Pick the baseline model
  - Select the algorithm – sampling, optimization, etc.
  - Specify how many Amazon resources (aka $) you want to throw at the problem
- **Once the spreadsheet is set up, a simple command:**
  - Fires up an Amazon cluster;
  - Automatically configures it with EnergyPlus, OpenStudio, etc;
  - And starts assigning individual simulations to worker CPUs
- **Your web browser lets you:**
  - Monitor progress,
  - Interact with results as they come in,
  - And download data for further analysis

Amazon Cloud Resources

	vCPU	ECU	Memory (GiB)	Instance Storage (GB)	Linux/UNIX Usage
General Purpose - Current Generation					
t2.micro	1	Variable	1	EBS Only	$0.013 per Hour
t2.small	1	Variable	2	EBS Only	$0.026 per Hour
t2.medium	2	Variable	4	EBS Only	$0.052 per Hour
m3.medium	1	3	3.75	1 x 4 SSD	$0.070 per Hour
m3.large	2	6.5	7.5	1 x 32 SSD	$0.140 per Hour
m3.xlarge	4	13	15	2 x 40 SSD	$0.280 per Hour
m3.2xlarge	8	26	30	2 x 80 SSD	$0.560 per Hour
Compute Optimized - Current Generation					
c4.large	2	8	3.75	EBS Only	$0.116 per Hour
c4.xlarge	4	16	7.5	EBS Only	$0.232 per Hour
c4.2xlarge	8	31	15	EBS Only	$0.464 per Hour
c4.4xlarge	16	62	30	EBS Only	$0.928 per Hour
c4.8xlarge	36	132	60	EBS Only	$1.856 per Hour
c3.large	2	7	3.75	2 x 16 SSD	$0.105 per Hour
c3.xlarge	4	14	7.5	2 x 40 SSD	$0.210 per Hour
c3.2xlarge	8	28	15	2 x 80 SSD	$0.420 per Hour
c3.4xlarge	16	55	30	2 x 160 SSD	$0.840 per Hour
c3.8xlarge	32	108	60	2 x 320 SSD	$1.680 per Hour

High Frequency Intel Xeon Processors operating at 2.5GHz with Turbo up to 3.3GHz

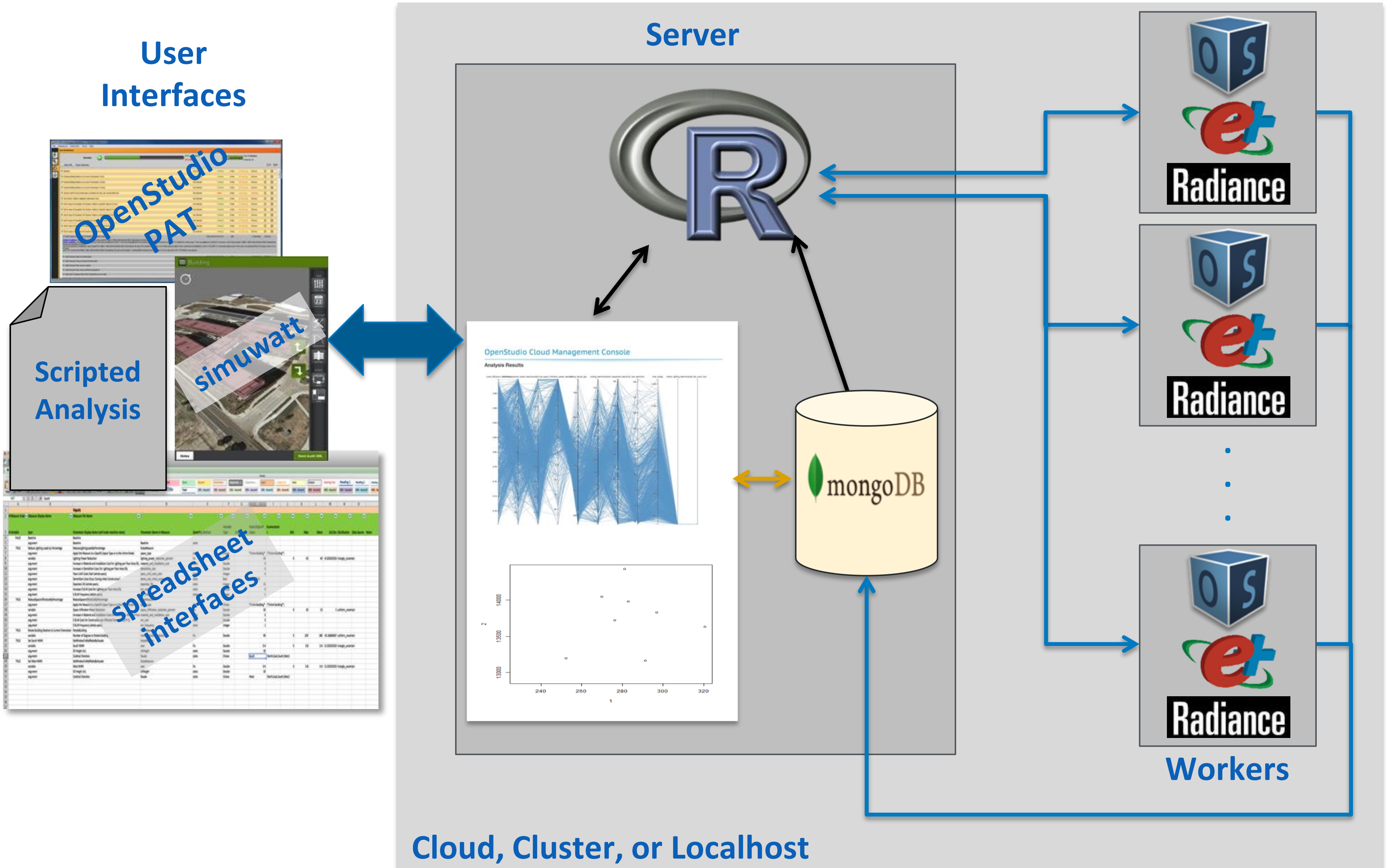
High Frequency Intel Xeon E5-2670 v2 (Ivy Bridge) Processors

High frequency Intel Xeon E5-2666 v3 (Haswell) processors

High Frequency Intel Xeon E5-2680 v2 (Ivy Bridge) Processors

http://aws.amazon.com/ec2/pricing/

OpenStudio Sever Architecture



OpenStudio Optimization Capability

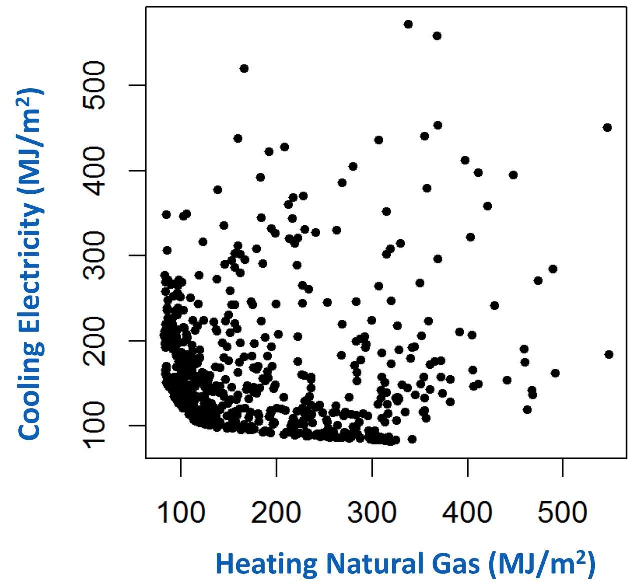
Multi-Objective Algorithms

NSGA2 (Non-dominated Sorting Genetic Algorithm)

- Parallel F evaluations
- Mixed Continuous or Discrete variables

SPEA2 (Strength Pareto Evolutionary Algorithm)

- Parallel F evaluations
- Continuous variables only



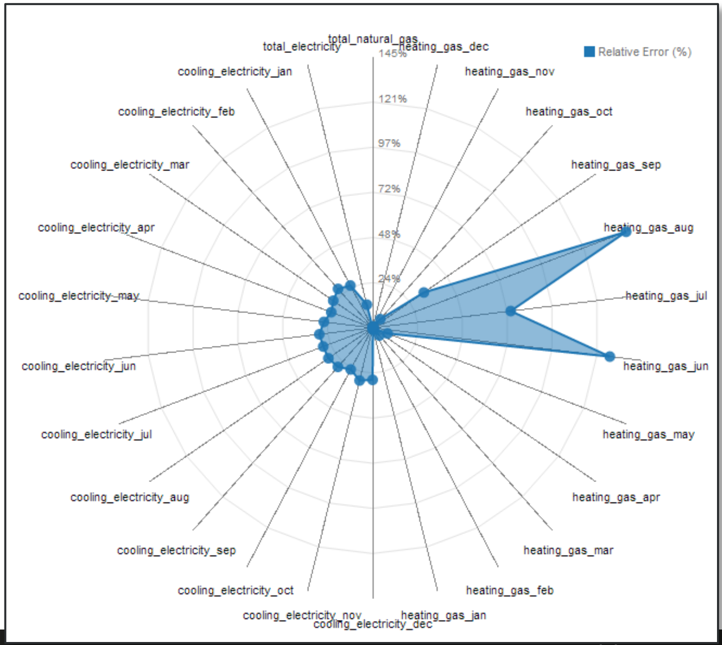
Single-Objective Algorithms

Rgenoud (GENetic Optimized Using Derivatives)

- Parallel F evaluations for genetic search
- Parallel gradient calculation for continuous variables

Optim (quasi-Newton method with bounds)

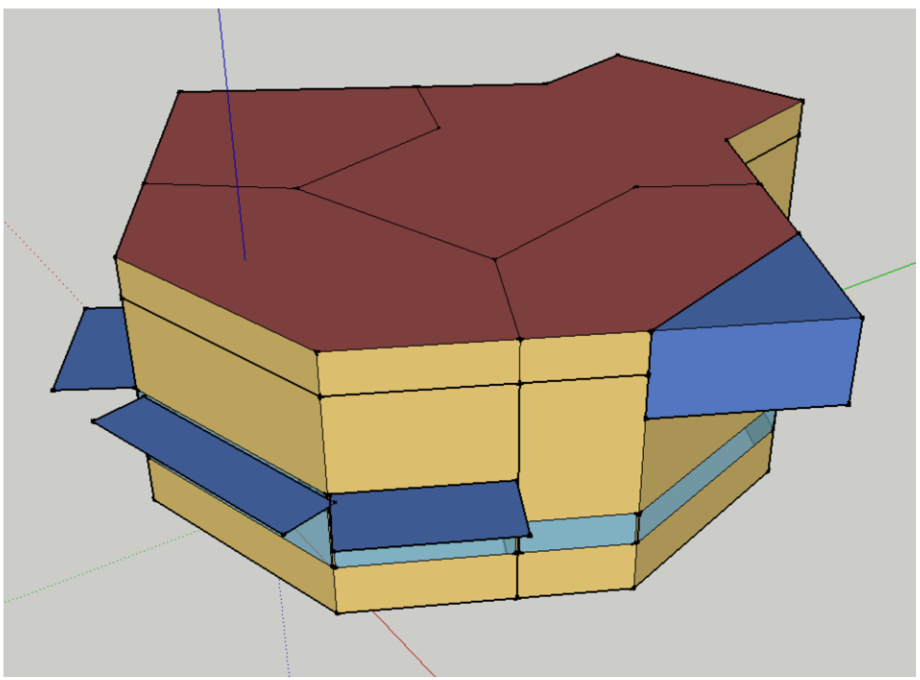
- Parallel gradient calculation
- Continuous variables only

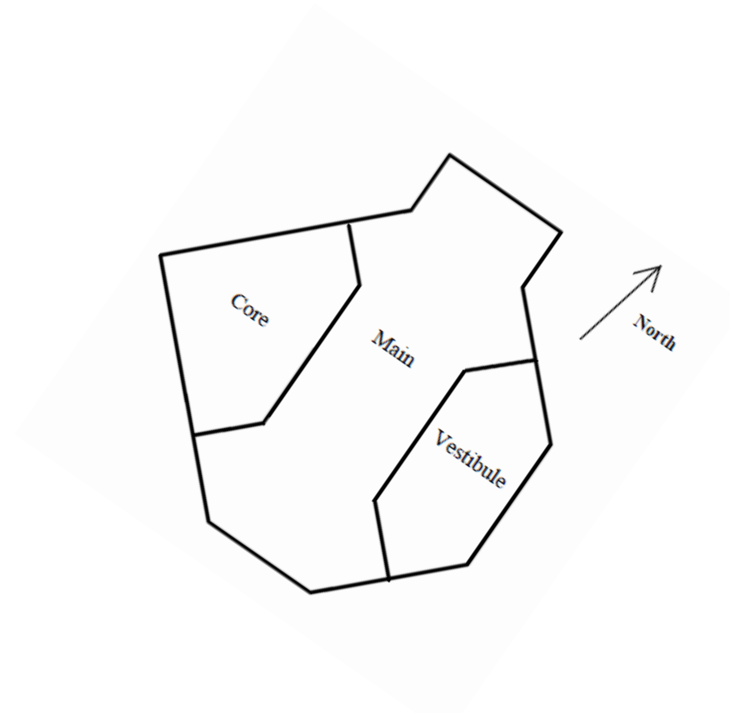


OpenStudio Calibration Example

NREL site entrance building

- Golden, CO
- 850 ft^2
- Built in 1994
- 1 story, Occupied 24hrs a day by 1-4 people
- Split system DX cooler with a natural gas furnace
- Baseboard electric heater by the badging window





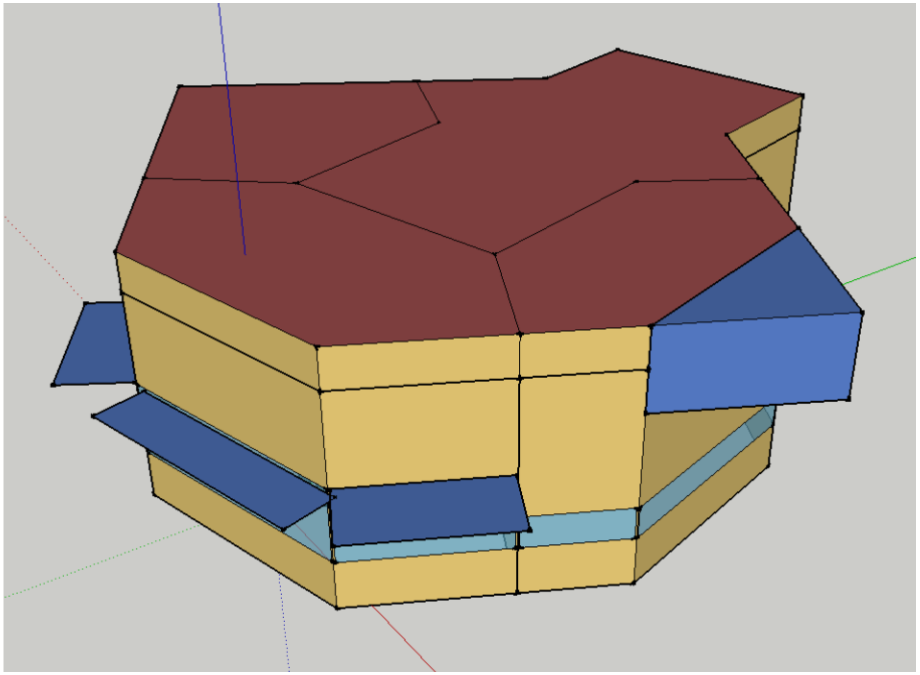
OpenStudio Calibration Example

Variables

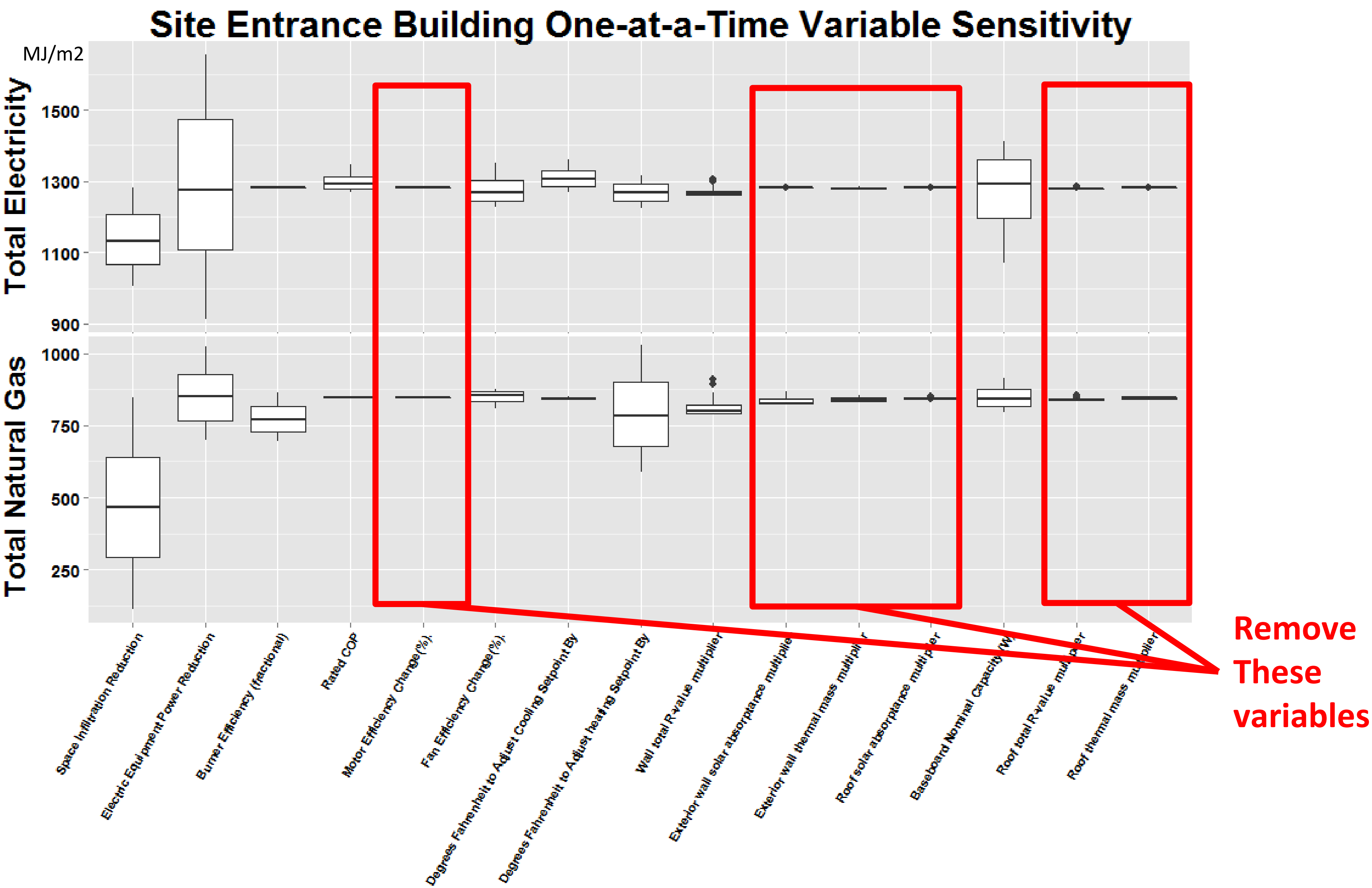
- Space Infiltration change (%)
- Electric Equipment Power change (%)
- Gas Burner Efficiency (%)
- DX Cooling Coil COP
- Fan Efficiency (%)
- Motor Efficiency (%)
- Electric Baseboard Capacity (W)
- Cooling Setpoint (F)
- Heating Setpoint (F)
- Wall R value
- Wall exterior solar absorptance
- Wall exterior thermal mass
- Roof R value
- Roof exterior solar absorptance
- Roof exterior thermal mass

Objective Functions

- Electric CVRMSE
- Electric NMBE
- Gas CVRMSE
- Gas NMBE



OpenStudio Calibration Example



OpenStudio Calibration Example

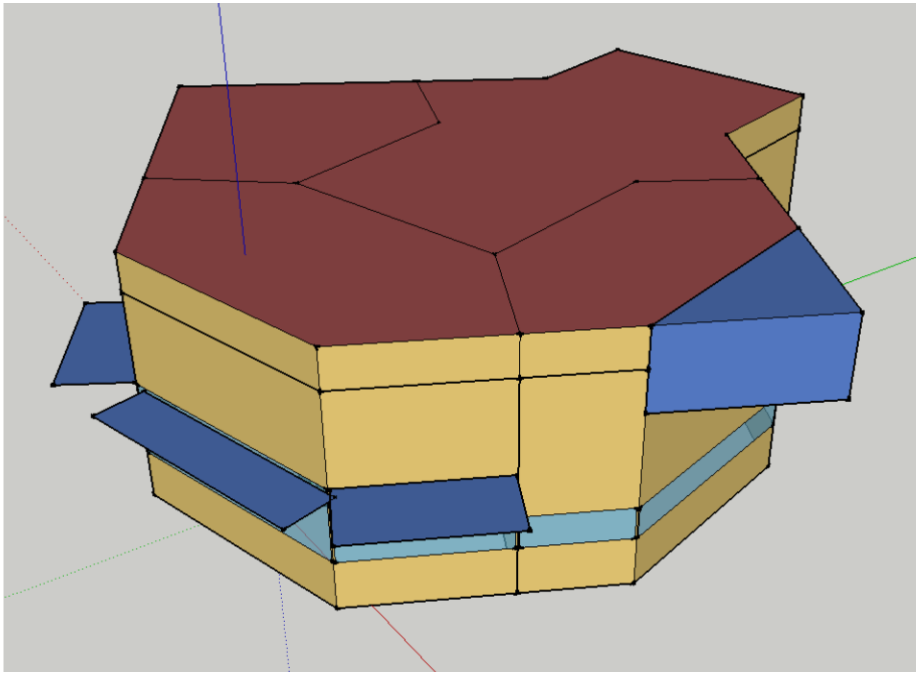
Variables

- Space Infiltration change (%)
- Electric Equipment Power change (%)
- Gas Burner Efficiency (%)
- DX Cooling Coil COP
- Fan Efficiency (%)
- ~~Motor Efficiency (%)~~
- Electric Baseboard Capacity (W)
- Cooling Setpoint (F)
- Heating Setpoint (F)
- Wall R value
- ~~Wall exterior solar absorptance~~
- ~~Wall exterior thermal mass~~
- ~~Roof R value~~
- ~~Roof exterior solar absorptance~~
- ~~Roof exterior thermal mass~~

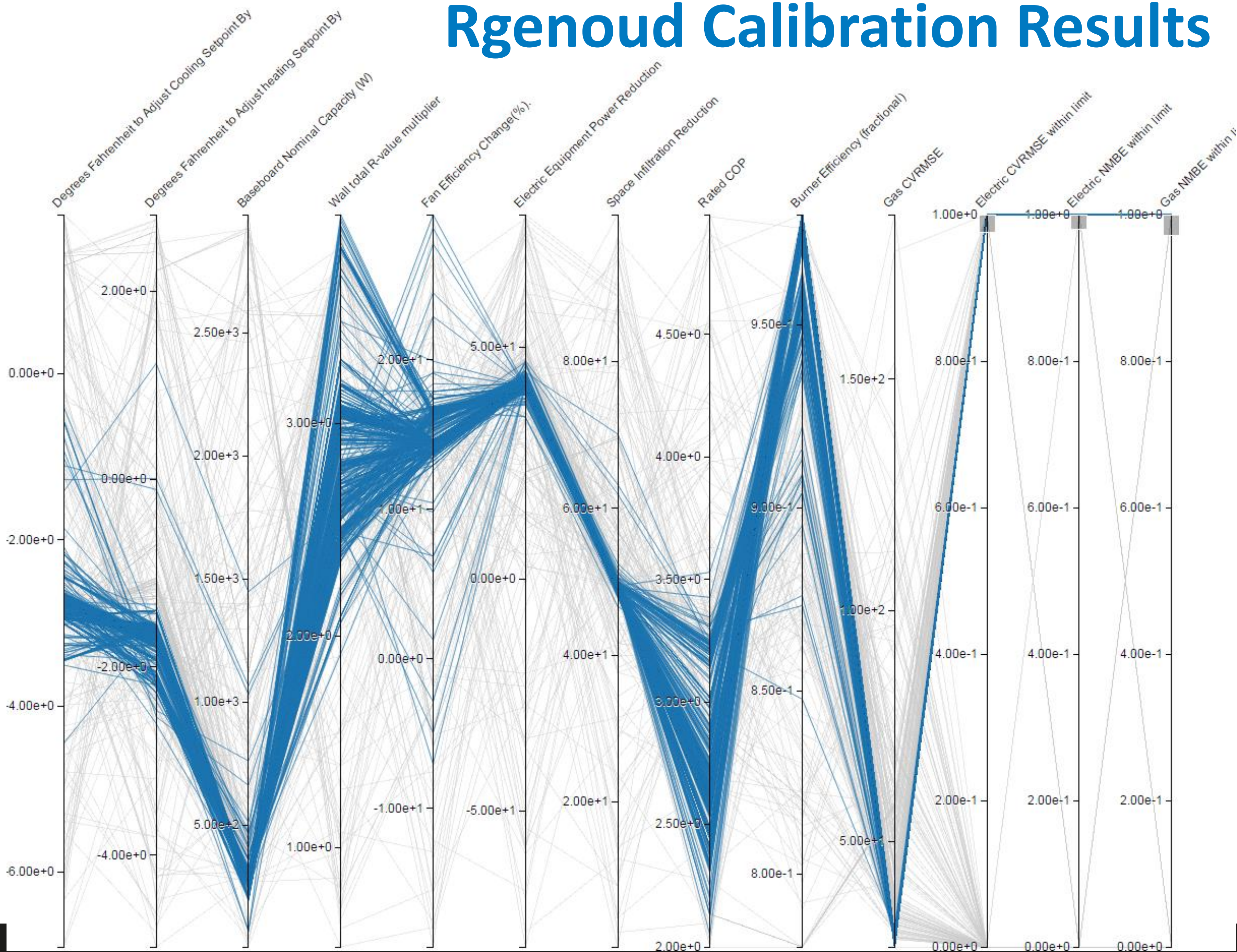
Reduced problem size from 15 to 9 variables

Objective Functions

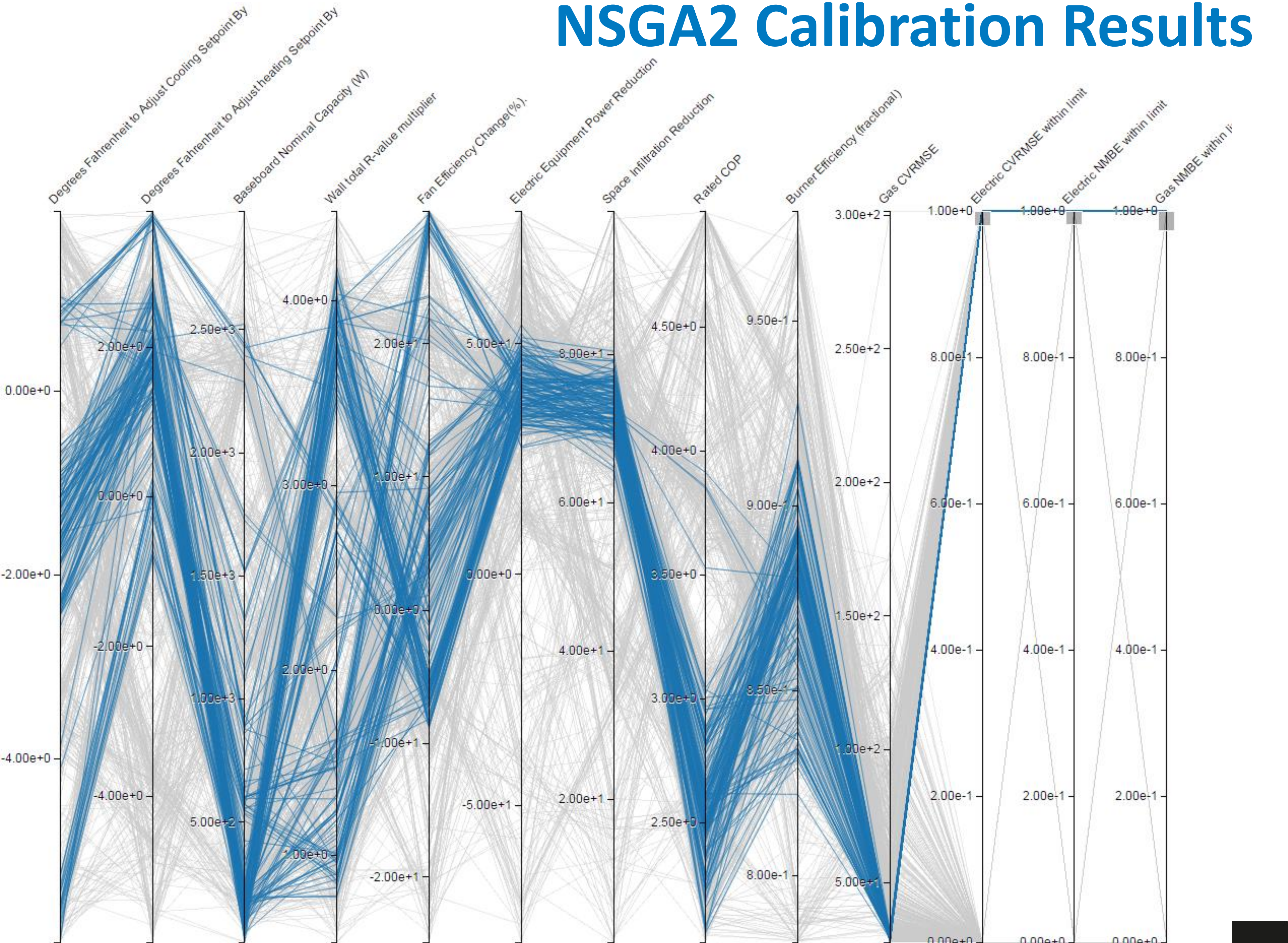
- Electric CVRMSE
- Electric NMBE
- Gas CVRMSE
- Gas NMBE



Rgenoud Calibration Results



NSGA2 Calibration Results

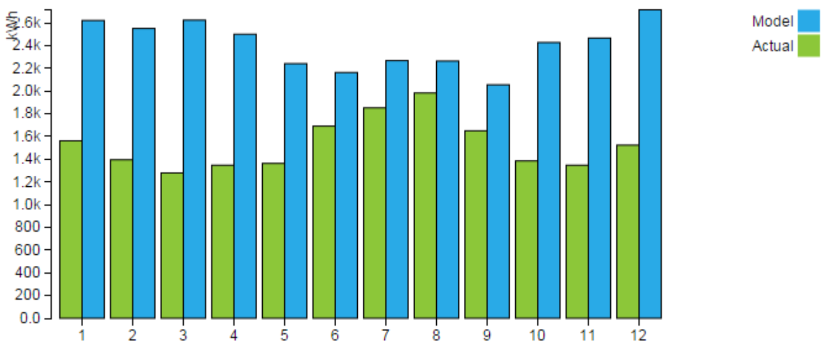


Seed model

Electricity Consumption (kWh)

CV(RMSE) = 64.58

NMBE = -62.42

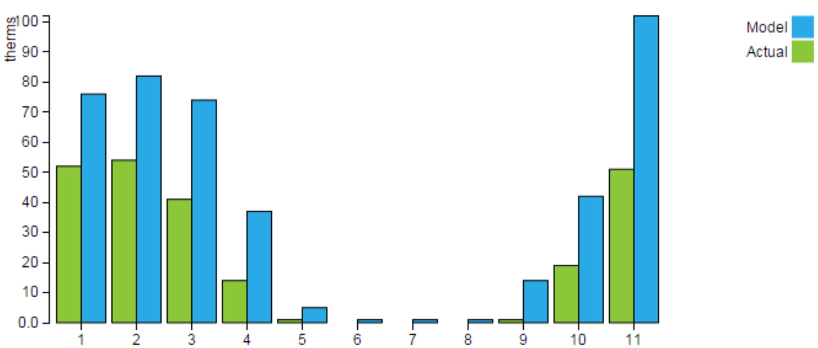


	1	2	3	4	5	6	7	8	9	10	11	12
Start	1/1	2/1	3/1	4/1	5/1	6/1	7/1	8/1	9/1	10/1	11/1	12/1
End	1/29	2/27	3/30	4/29	5/30	6/29	7/30	8/30	9/29	10/30	11/29	12/30
Actual	1,562	1,395	1,279	1,347	1,363	1,691	1,852	1,983	1,650	1,385	1,347	1,524
Model	2,621	2,551	2,624	2,500	2,241	2,163	2,268	2,264	2,055	2,427	2,466	2,715
NMBE	67.77%	82.89%	105.18%	85.56%	64.41%	27.93%	22.48%	14.15%	24.53%	75.24%	83.05%	78.13%

Natural Gas Consumption (therms)

CV(RMSE) = 118.50

NMBE = -95.49



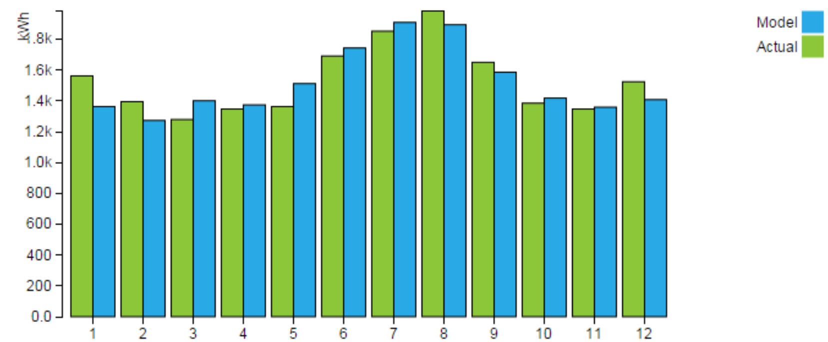
	1	2	3	4	5	6	7	8	9	10	11
Start	1/18	2/19	3/19	4/18	5/17	6/18	7/18	8/19	9/17	10/16	11/14
End	2/17	3/17	4/16	5/15	6/16	7/16	8/17	9/15	10/14	11/12	12/16
Actual	52	54	41	14	1	—	—	—	1	19	51
Model	76	82	74	37	5	1	1	1	14	42	102
NMBE	45.83%	51.92%	81.07%	167.65%	389.45%	—	—	—	1,345.08%	121.37%	99.22%

Calibrated model

Electricity Consumption (kWh)

CV(RMSE) = 6.96

NMBE = 0.82

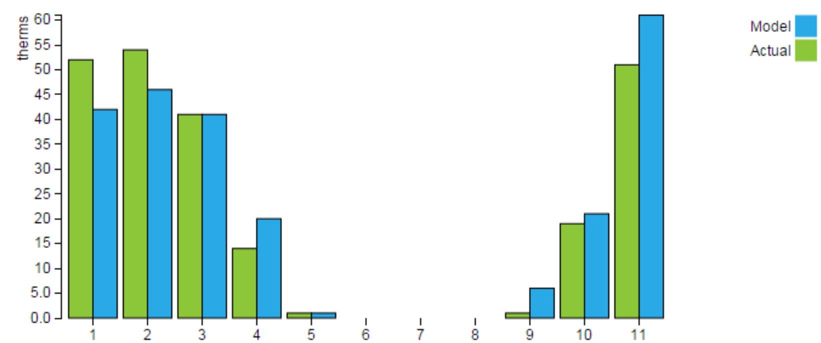


	1	2	3	4	5	6	7	8	9	10	11	12
Start	1/1	2/1	3/1	4/1	5/1	6/1	7/1	8/1	9/1	10/1	11/1	12/1
End	1/29	2/27	3/30	4/29	5/30	6/29	7/30	8/30	9/29	10/30	11/29	12/30
Actual	1,562	1,395	1,279	1,347	1,363	1,691	1,852	1,983	1,650	1,385	1,347	1,524
Model	1,363	1,273	1,401	1,374	1,512	1,743	1,909	1,894	1,586	1,418	1,359	1,408
NMBE	-12.76%	-8.76%	9.52%	2.01%	10.93%	3.05%	3.1%	-4.48%	-3.86%	2.37%	0.9%	-7.58%

Natural Gas Consumption (therms)

CV(RMSE) = 26.93

NMBE = -2.83



	1	2	3	4	5	6	7	8	9	10	11
Start	1/18	2/19	3/19	4/18	5/17	6/18	7/18	8/19	9/17	10/16	11/14
End	2/17	3/17	4/16	5/15	6/16	7/16	8/17	9/15	10/14	11/12	12/16
Actual	52	54	41	14	1	—	—	—	1	19	51
Model	42	46	41	20	1	—	—	—	6	21	61
NMBE	-19.05%	-14.62%	0.33%	41.77%	11.44%	—	—	—	473.48%	12.97%	19.83%

OpenStudio Calibration Example

Each model took around 40 seconds to run
Computer used was 24 core 2.7GHZ workstation

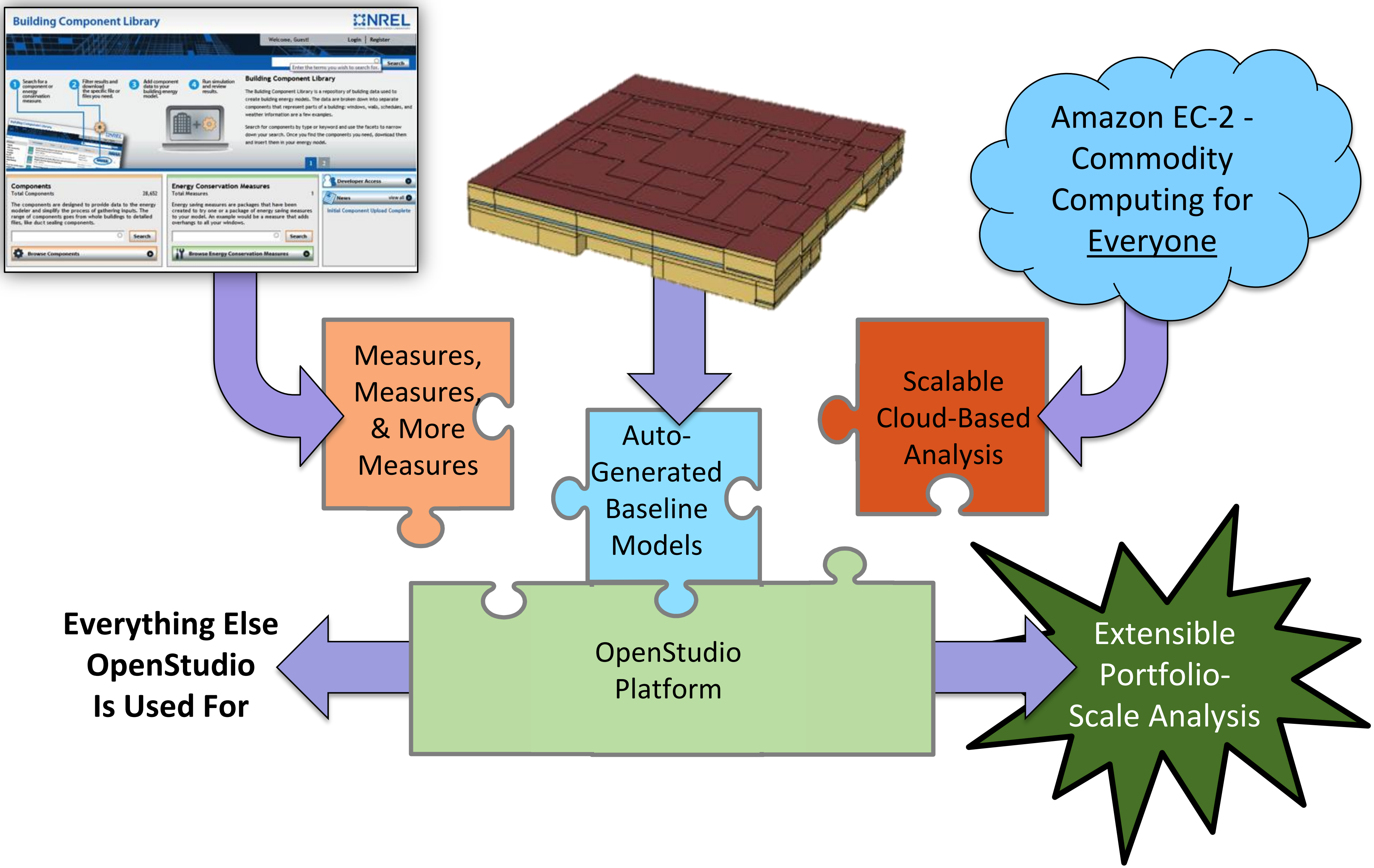
Rgenoud ran 1489 simulations in 1.4 hrs
NSGA2 ran 1408 simulations in <1 hr

Approx Cost to run on AWS EC2:
$3.36
$1.68

"Best" variable values were:

Field Name	Field Value
Degrees Fahrenheit to Adjust Cooling Setpoint By	-2.94643457641175
Degrees Fahrenheit to Adjust heating Setpoint By	-1.54769680521238
Baseboard Nominal Capacity (W)	205.95356118088
Wall total R-value multiplier	3.15853308649533
Fan Efficiency Change(%).	14.6328726489339
Electric Equipment Power Reduction	41.6787823386049
Space Infiltration Reduction	49.0936344864588
Rated COP	2.59119407956713
Burner Efficiency (fractional)	0.979999593097956

Putting All the Pieces Together…



Conclusions

- OpenStudio measure based workflow is a powerful way to leverage both model creation and model optimization / calibration capabilities.
- Genetic based algorithms provide good insight into the sensitivity of the variable space.
- Better calibration results could possibly be had by varying schedule parameters.

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