Hybrid Calibration Methodology for Building Energy Models Coupling Sensor Data and Stochastic Modeling

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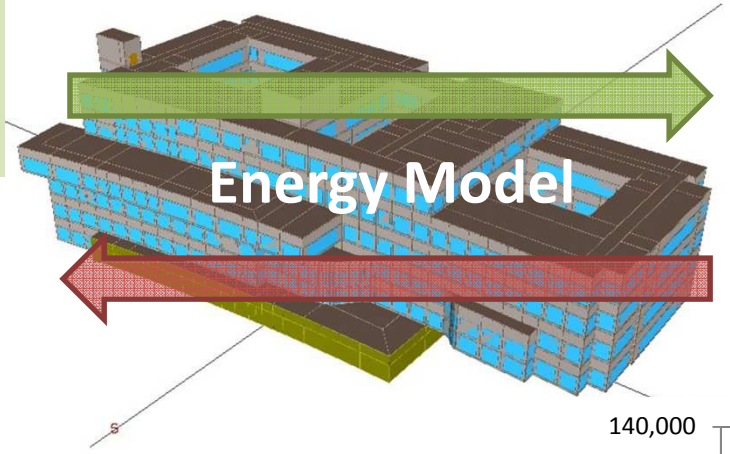
Building Simulation

Inputs:
- Weather
- Geometry
- Envelope Properties
- HVAC Systems
- …

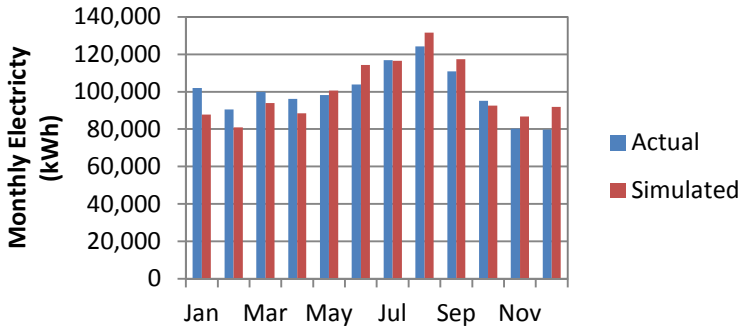
Forward problem



Outputs:
- Energy
- Thermal Comfort
- Daylighting
- …

Unknowns:
- HVAC Efficiency
- Building Leakage
- …

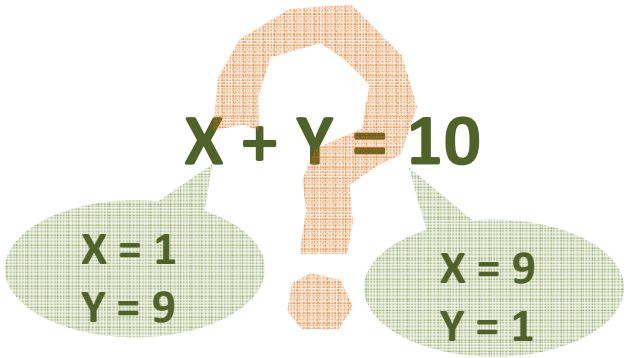
Inverse problem



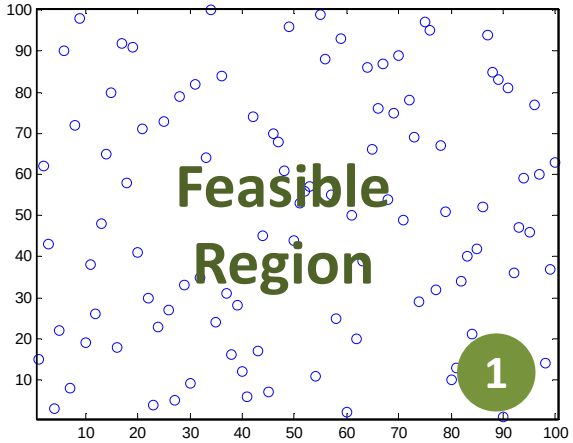
The Challenges

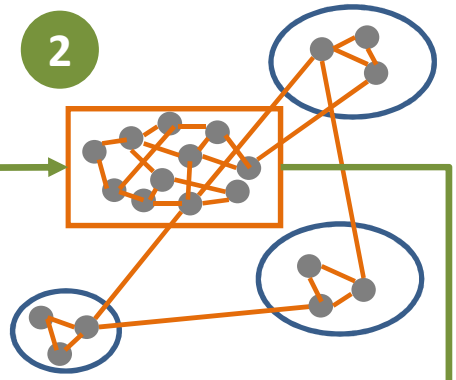
```
Simulation Parameters
---------------------
[------] Version
[------] SimulationControl
[------] Building
[------] ShadowCalculation
[------] SurfaceConvectionAlgorithm:Inside
[------] SurfaceConvectionAlgorithm:Outside
[------] HeatBalanceAlgorithm
[------] HeatBalanceSettings:ConductionFiniteDifference
[------] ZoneAirHeatBalanceAlgorithm
[------] ZoneAirContaminantBalance
[------] ZoneCapacitanceMultiplier:ResearchSpecial
[------] Timestep
[------] ConvergenceLimits
[------] ProgramControl

Compliance Objects
------------------
[------] Compliance:Building

Location and Climate
--------------------
[------] Site:Location
[------] SizingPeriod:DesignDay
[------] SizingPeriod:WeatherFileDays
[------] SizingPeriod:WeatherFileConditionType
[------] RunPeriod
[------] RunPeriod:CustomRange
[------] RunPeriodControl:SpecialDays
[------] RunPeriodControl:DaylightSavingTime
[------] WeatherProperty:SkyTemperature
[------] Site:WeatherStation
[------] Site:HeightVariation
[------] Site:GroundTemperature:BuildingSurface
[------] Site:GroundTemperature:FCfactorMethod
[------] Site:GroundTemperature:Shallow
[------] Site:GroundTemperature:Deep
[------] Site:GroundReflectance
[------] Site:GroundReflectance:SnowModifier
[------] Site:WaterMainsTemperature
[------] Site:Precipitation
[------] RoofIrrigation

Schedules
---------
[------] ScheduleTypeLimits
[------] Schedule:Day:Hourly
[------] Schedule:Day:Interval
[------] Schedule:Day:List
[------] Schedule:Week:Daily
[------] Schedule:Week:Compact
[------] Schedule:Year
[------] Schedule:Compact
[------] Schedule:Constant
[------] Schedule:File

Surface Construction Elements
```

An underdetermined problem



A Stochastic Approach





Bldg. Models

Utility Bills

M&V calibration criteria 4

Calibrated Model Set 5

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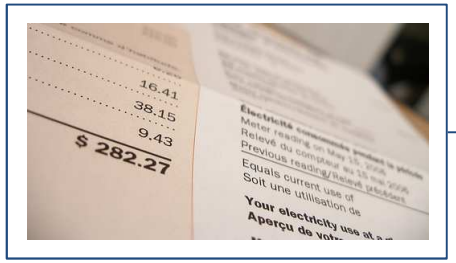
Methodology



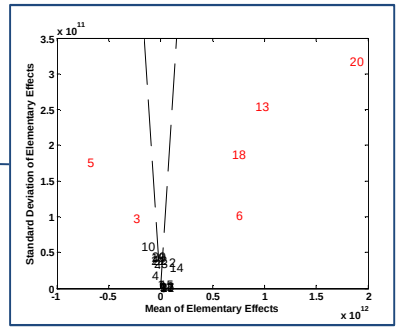
1 Collect Data

2 Deploy Sensors

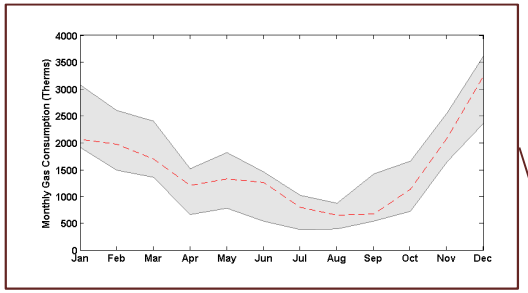
3 Develop Energy Model

EnergyPlus

4 Sensitivity Analysis



5 Stochastic Modeling



6 Identify Plausible Solutions

7 Project Energy Savings

Case Study Building

Building Data

- City Hall located East of downtown Portland
- Gross floor area of 85,000 ft^2
- Constructed in 1995
- Steel frame structure, concrete floors, and tile exterior

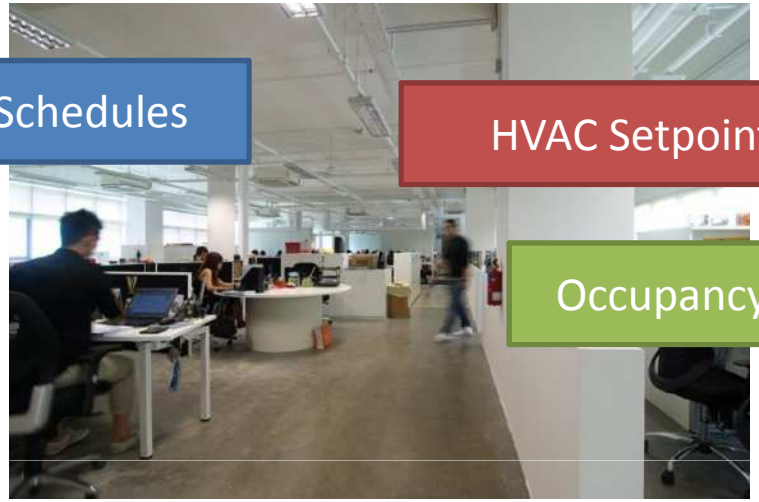
HVAC System

- Two packaged variable air volume (VAV) units with terminal reheat boxes
- DX cooling system
- Gas fired boiler

Sensor Data

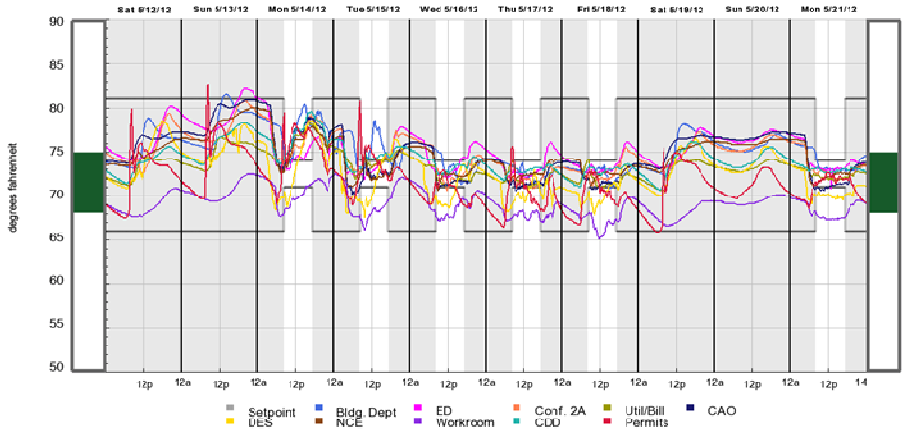
Indoor environment sensors :

- Air temperature
- Relative Humidity
- Carbon dioxide level
- Light intensity

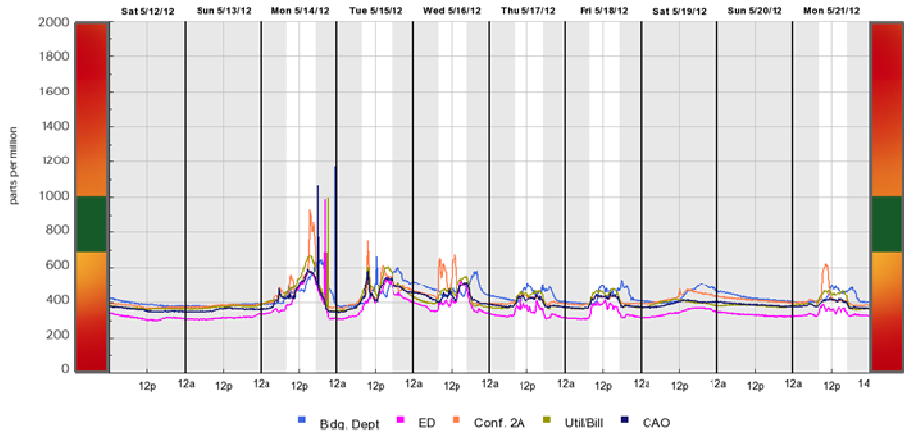


Smart meters can be used to collect 15-min interval (whole building) electricity data.

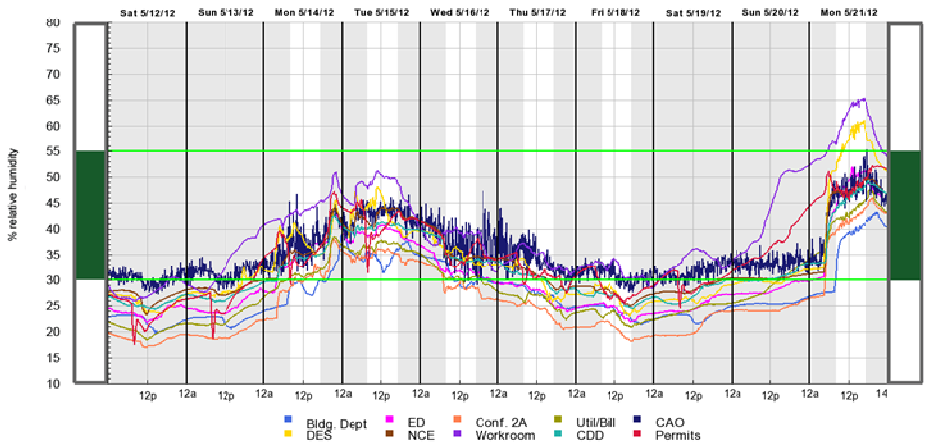
Short-term Sensor Data



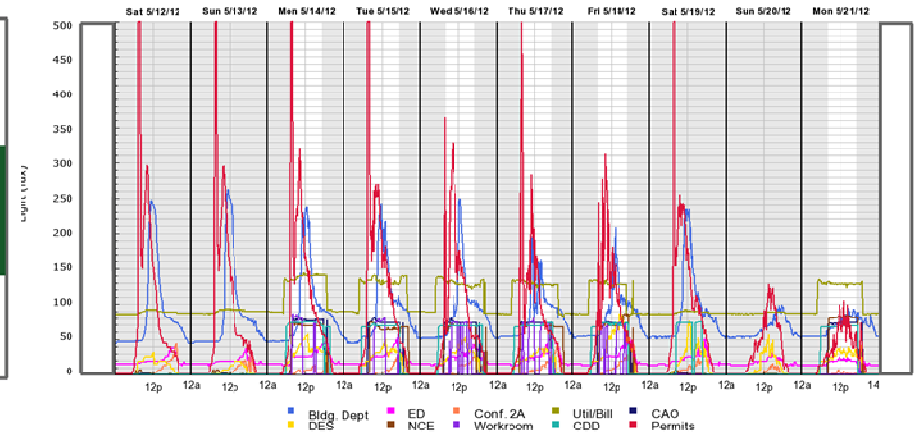
Temperature



Carbon Dioxide



Humidity



Light Intensity

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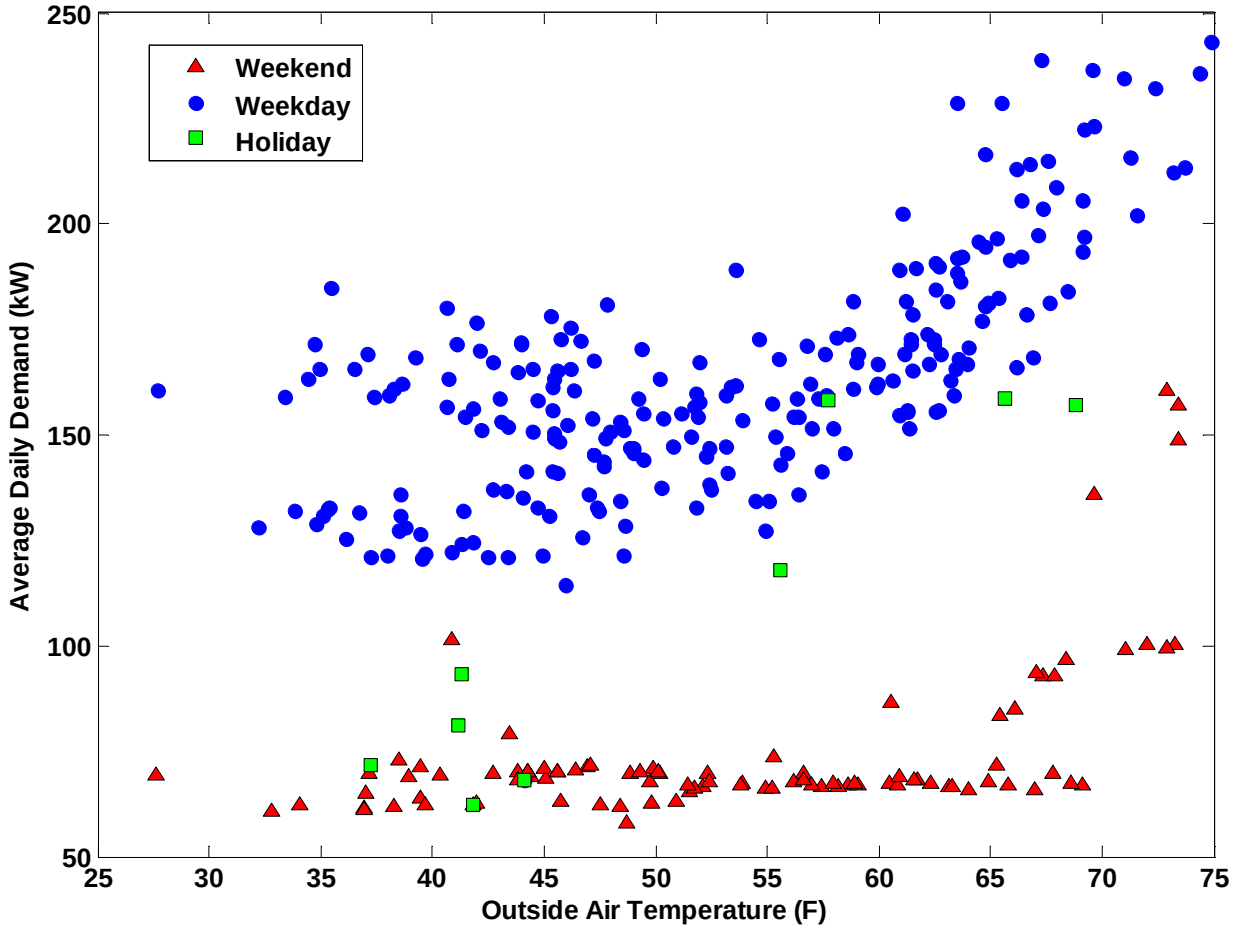
Smart Meter Data



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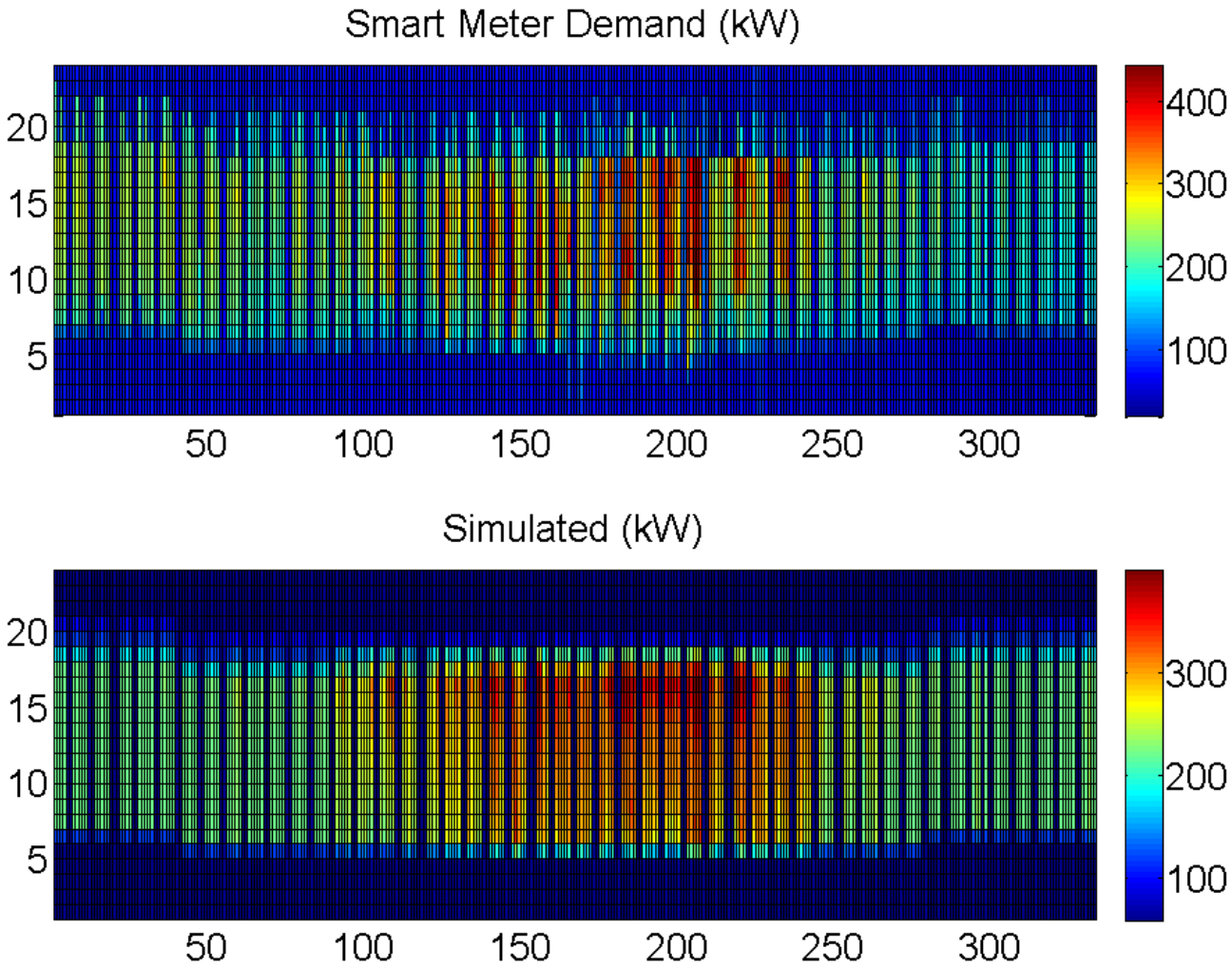
Building Energy Model

- Developed using EnergyPlus
- Actual Meteorological Year (AMY) Weather file
- Inputs defined based on data collected from the building
- Building operation patterns verified with deployed sensor data

Smart Meter Data



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Uncertain Parameters

#	Variables	Units	Ref	Min	Max
1	Insulation R-Value	m^2-K/W	2.11	1.76	3.52
2	Window U-Factor	W/m^2-K	3.01	2.67	3.97
3	Window SHGC	-	0.70	0.39	0.79
4	Occupant density	people/m^2	0.020	0.015	0.030
5	Combined Plugs and Light Density	W/ft^2	25	17	26
6	Infiltration Rate	ACH	0.24	0.00	1.00
7	Outdoor Air Flow Rate	m^3/s/person	0.015	0.009	0.028
8	Total Fan Efficiency	-	0.60	0.58	0.72
9	Cooling Coil COP	W/W	2.50	2.40	2.96
10	Boiler Efficiency	-	0.78	0.70	0.80
11	Boundary Layer Thinkness	m	305	274	366
12	Boundary Layer Coefficient	-	0.20	0.14	0.22

#	Variables	Units	Ref	Min	Max
13	Heating Setpoint	˚C	22	20	22.5
14	Heating Setback	˚C	19	18	20
15	Cooling Setpoint	˚C	23	22.5	24
16	Cooling Setback	˚C	26	24	28
17	Specific Fan Power	CFM/W	1.43	1.07	1.79
18	Equipment Radiant Fraction	-	0.3	0.1	0.8
19	Cooling Supply Air Temperature	˚C	7.5	7.0	13
20	Constant Minimum Flow Fraction	-	0.5	0.2	0.7

Sensitivity Analysis

Several different approaches exist

- *Sensitivity Analysis,* Salteli (2000)

Elementary Effect (EE) methodology

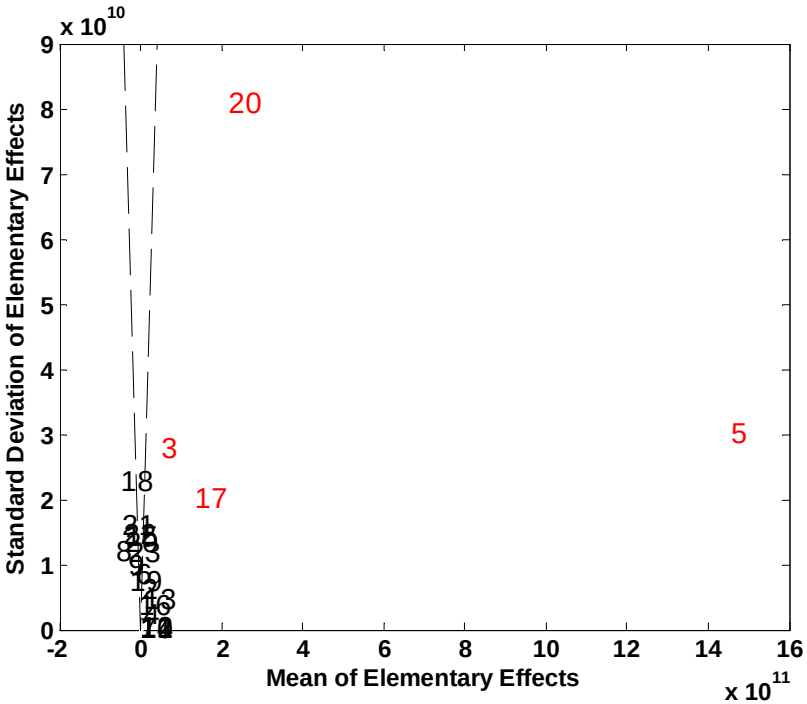
- One-at-a-time (OAT) screening process

Provides two sensitivity measures for each factor:

- Mean
- Standard deviation

$$EE_i(x_i,\ldots,x_k) = \frac{[y(x_1,x_2,\ldots,x_{i-1},x_i+\Delta x_{i+1},\ldots,x_k) - y(x_1,\ldots,x_k)]}{\Delta}$$

Sensitivity Analysis



Annual Electricity Consumption

[5] Combined plug and light load density
[20]Constant minimum flow fraction
[3] Window SHGC
[17] Specific fan power

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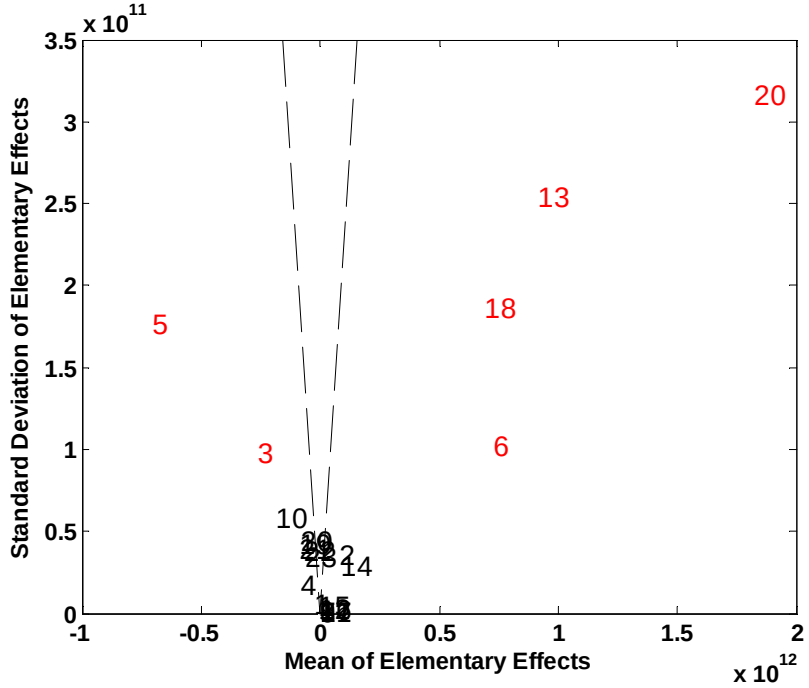
Sensitivity Analysis



Annual Gas Consumption

[5] Combined plug and light load density
[20]Constant minimum flow fraction
[6] Infiltration rate
[18] Equipment radiant fraction
[10] Boiler efficiency
[3] Window SHGC
[13] Heating Setpoint

Calibration Criteria

Based on ASHRAE Guideline 14

Calibrated model relative to monthly data:

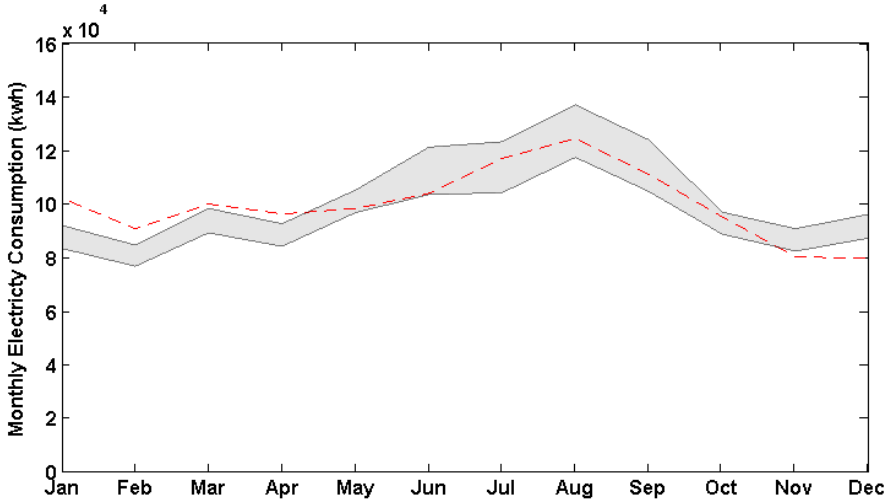
- NMBE < 5%
- CV(RSME) < 15%

$$NMBE = \frac{\sum_{1}^{n}(y_i - \hat{y}_i)}{(n-1)\times \bar{y}} \times 100$$

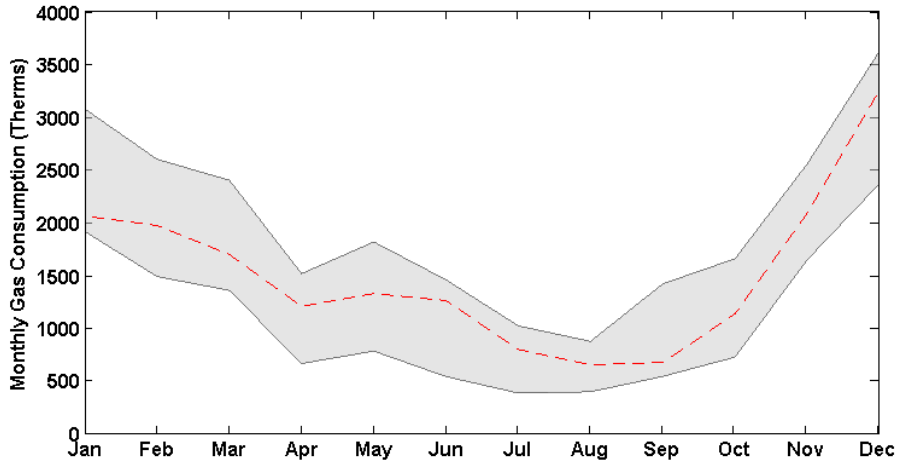
$$CV(RSME) = \sqrt{\frac{\sum_{1}^{n}(y_i - \hat{y}_i)}{(n-1)}} / \bar{y} \times 100$$

Calibration

- 505/10,000 samples meet the calibration criteria (NMBE < 5%, CV(RSME) < 15%)



Monthly Electricity Consumption



Monthly Gas Consumption

Conclusions

Short and long term sensor data is used to capture key building operation characteristics.

Sensitivity analysis determines weak and influential parameters.

Stochastic modeling is used to find a set of plausible solutions rather than a single “best fit” model.

Acknowledgements

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Questions?