Improving Model Calibration Using Inverse Modeling

International Building
Performance Simulation Association

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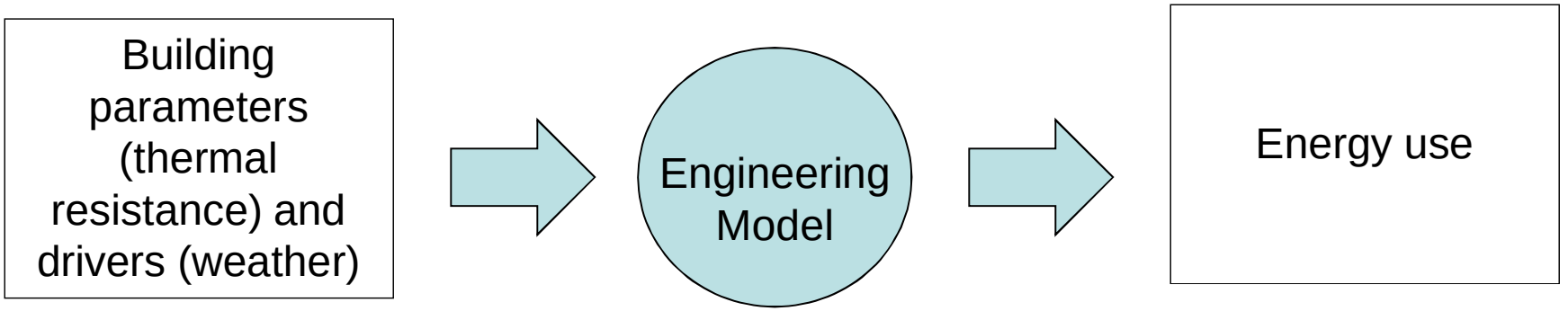
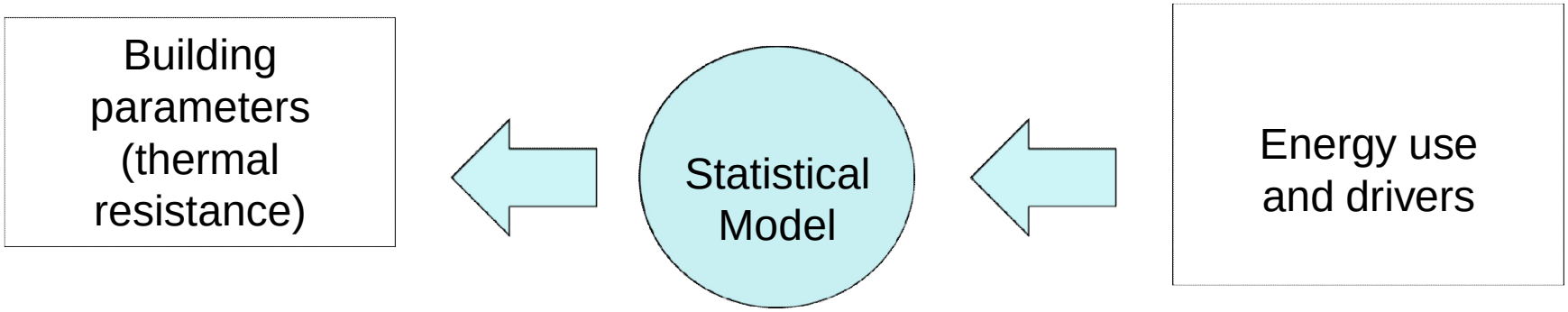
‘Inverse Modeling’

Traditional ‘forward’ modeling:



‘Inverse’ modeling:



Data Requirements

Monthly electricity and fuel bills

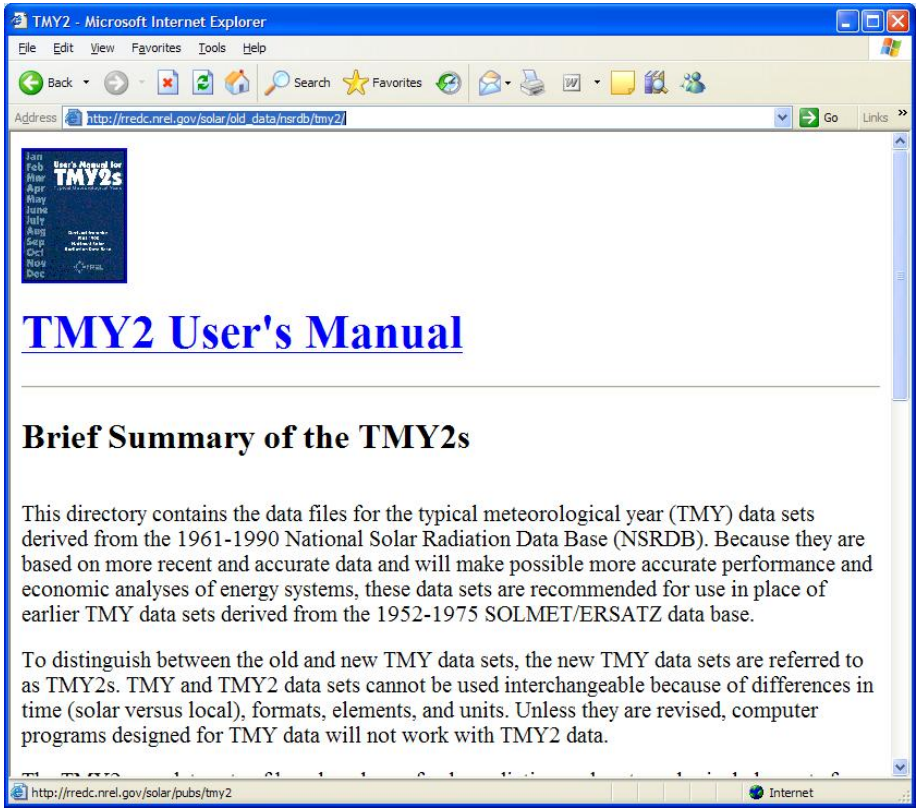
Influential variables (optional)

- Floor area, occupancy, etc.

Actual outdoor air temperature

Typical outdoor air temperature

Actual and Typical Outdoor Air Temperature Data



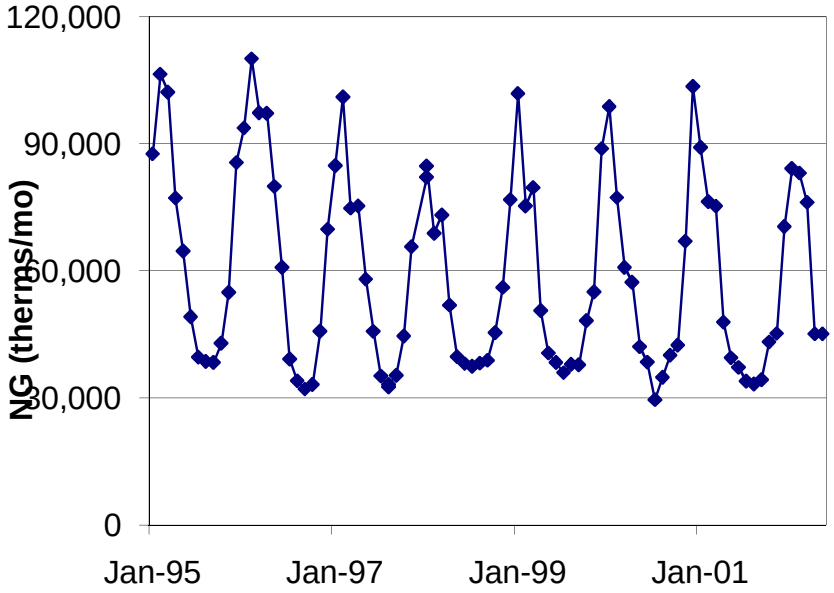
http://www.engr.udayton.edu/weather

http://rredc.nrel.gov/solar/old_data/nsrdb/tmy2

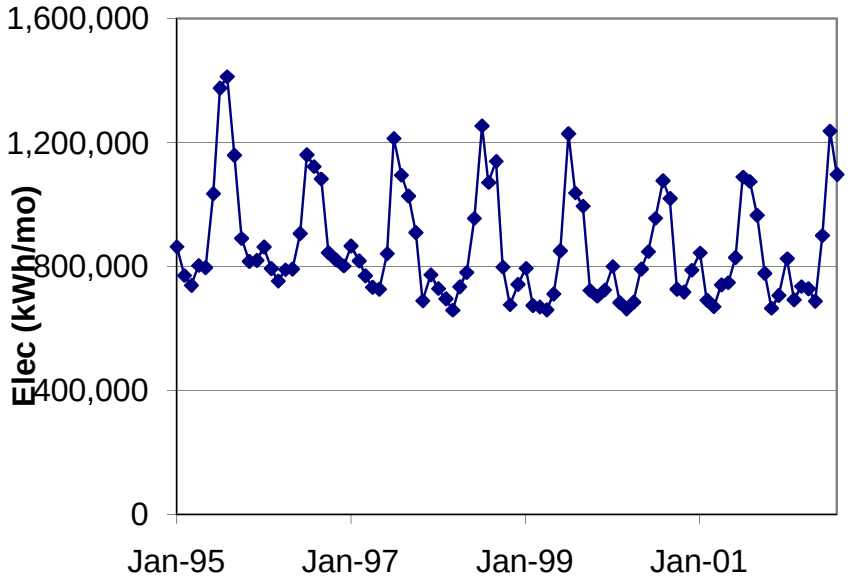
Step 1: Characterize Performance with ‘Energy Signature’ Model

- Develop 3PC or 3PH energy signature model

Seven Years of Hospital Monthly Fuel and Electricity Use

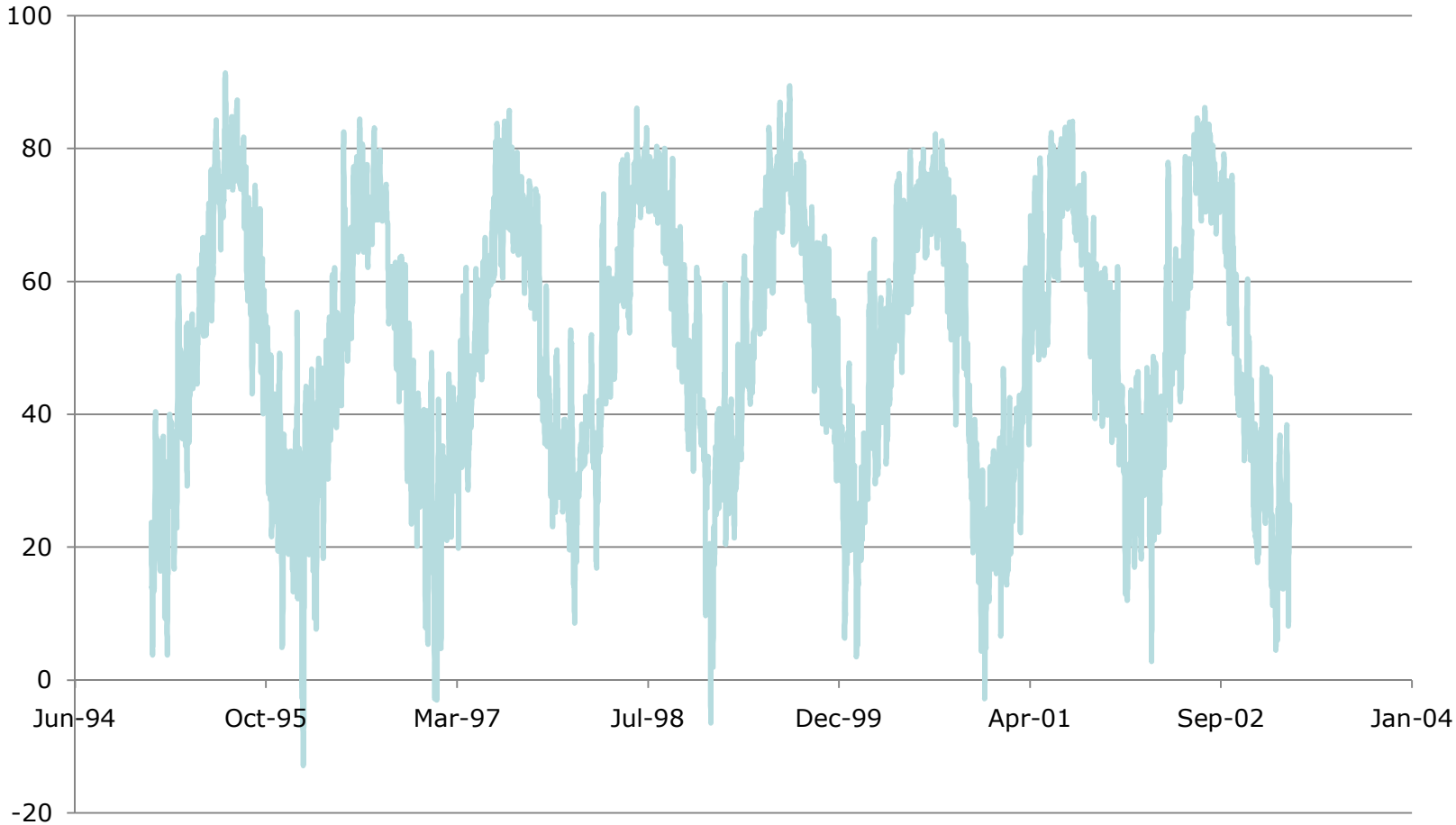


7 Years of Natural Gas Use

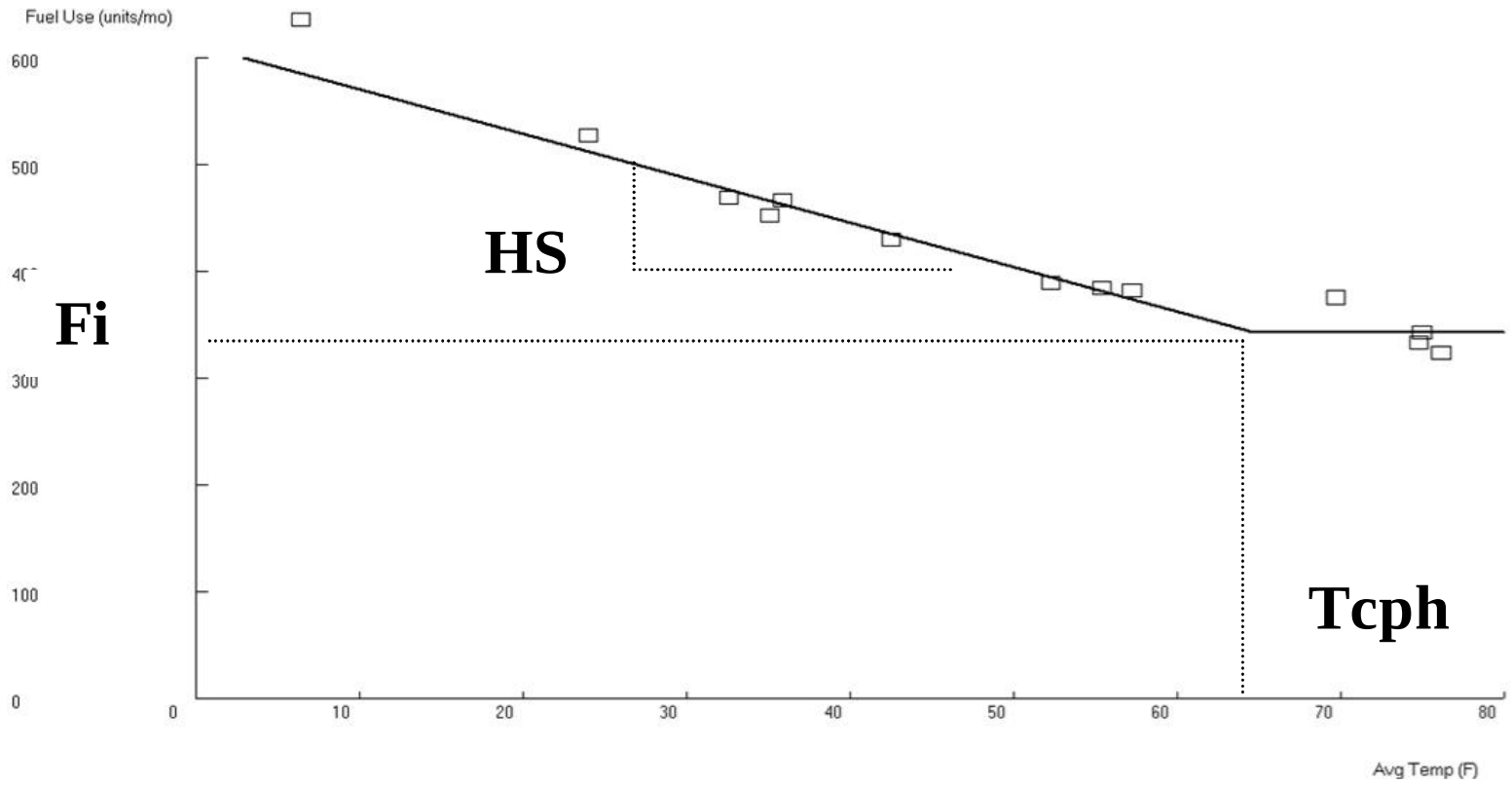


7 Years of Electricity Use

Seven Years of Daily Temperatures for Hospital Location

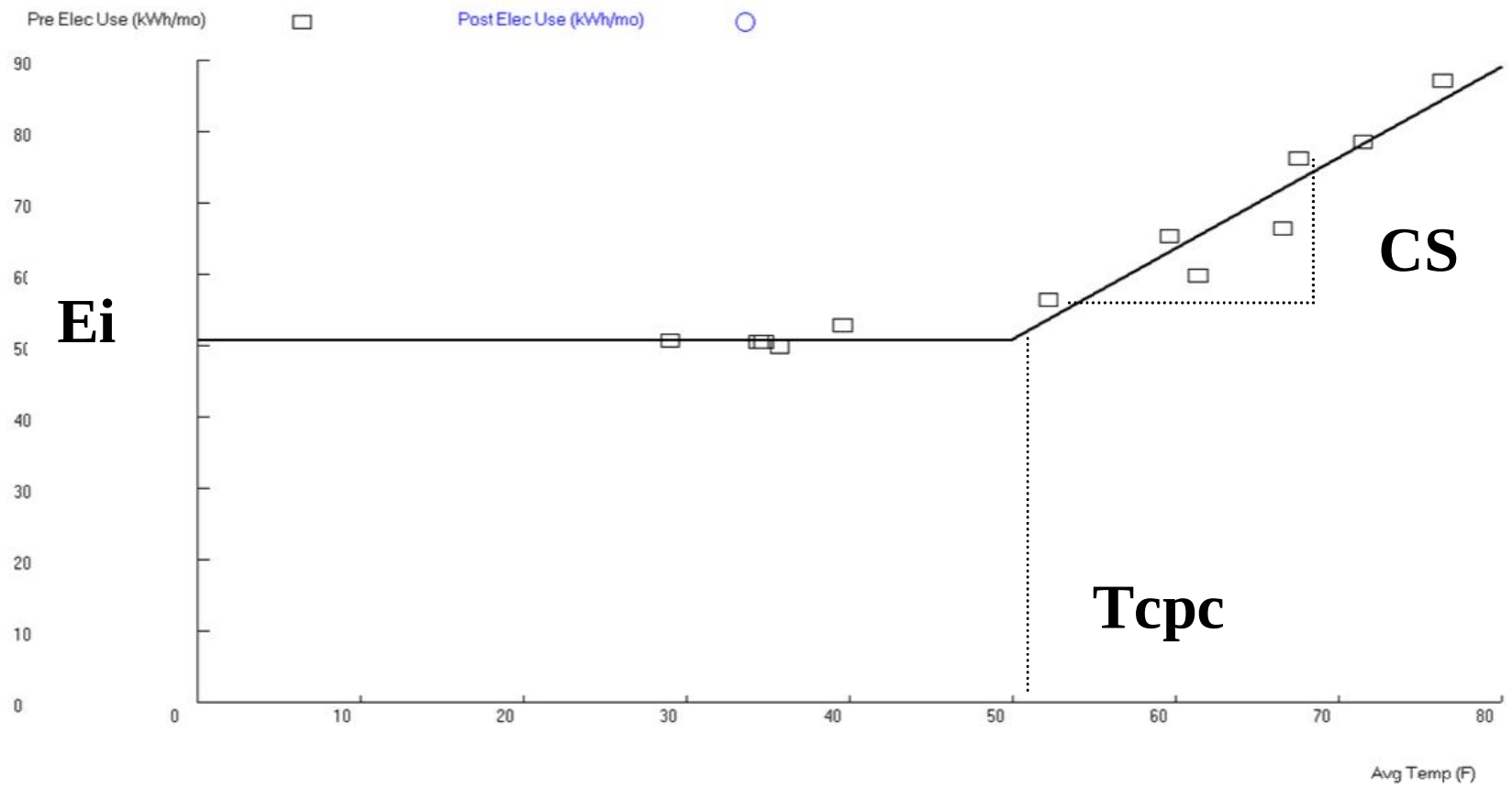


Hospital
Three-parameter Heating (3PH) Model



$$F = Fi + HS\,(Tcph - Toa)^{+}$$

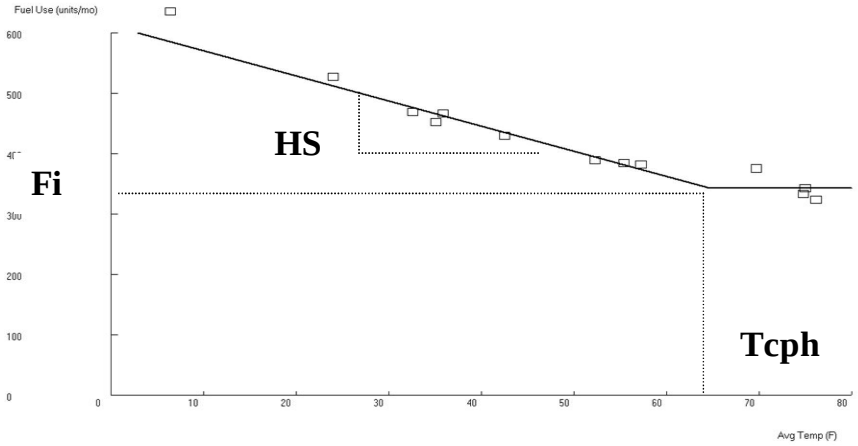
Hospital
Three-parameter Cooling (3PC) Model

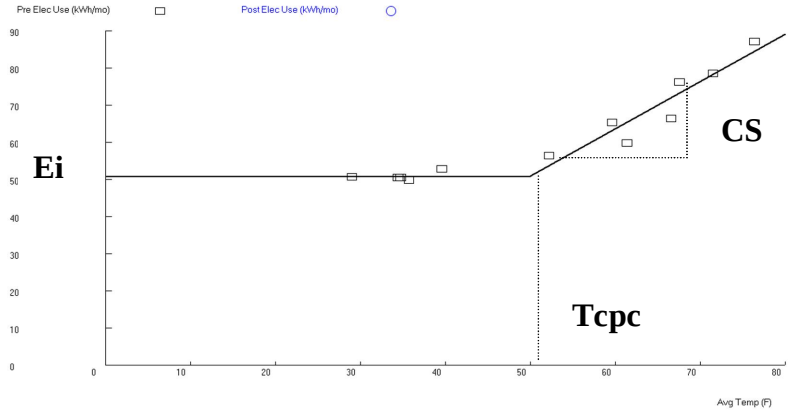


$$E = Ei + CS\,(Toa - Tcpc)^{+}$$

Physical Interpretation of Coefficients

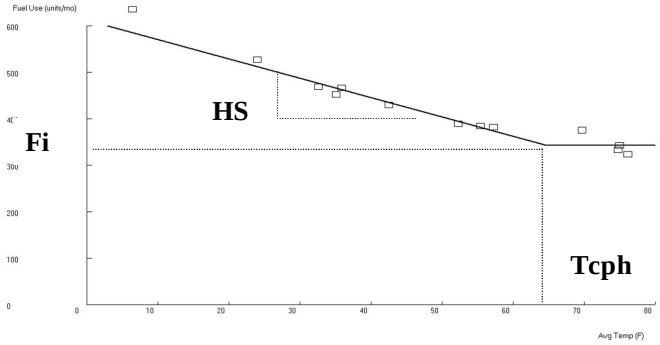
- Independent energy use: Fi and Ei
  - Fi is function of hot water, process heating, etc.
  - Ei is function of lights, plug loads, etc.

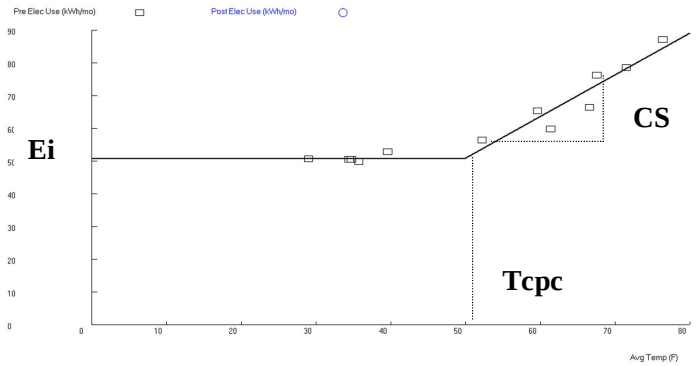




Physical Interpretation of Coefficients

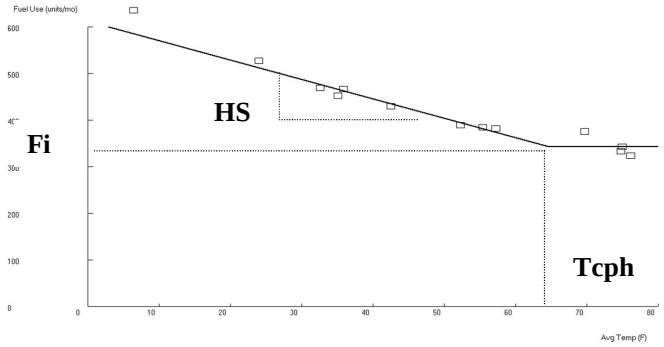
- Heating and cooling slope: HS and CS
  - Heating/cooling energy per degree of temperature
  - Slopes function of:
    - Envelope heat loss/gain: HC = CC = UA + V p cp
    - Efficiency of heating/cooling equipment: Effh and Effc
  - HS = HC / Effh CS = CC /Effc

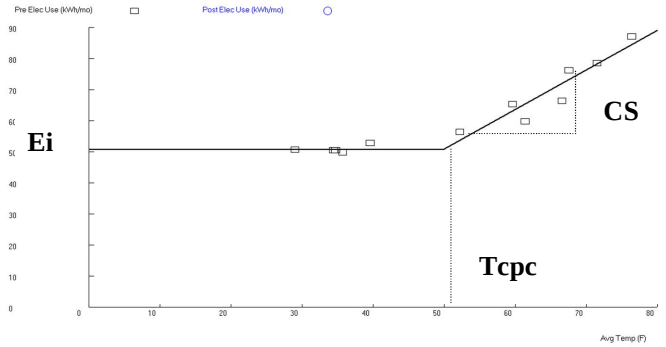




Physical Interpretation of Coefficients

- Balance temperature: Tbh and Tbc
  - Outdoor temperature where heating/cooling begins
  - Function of:
    - Thermostat set point: Tsp
    - Internal heat gain: Qi
  - Tbh = Tsp – Qi/HC Tbc = Tsp – Qi/CC





Skeptical?

How well can a simple model characterize building energy use, using

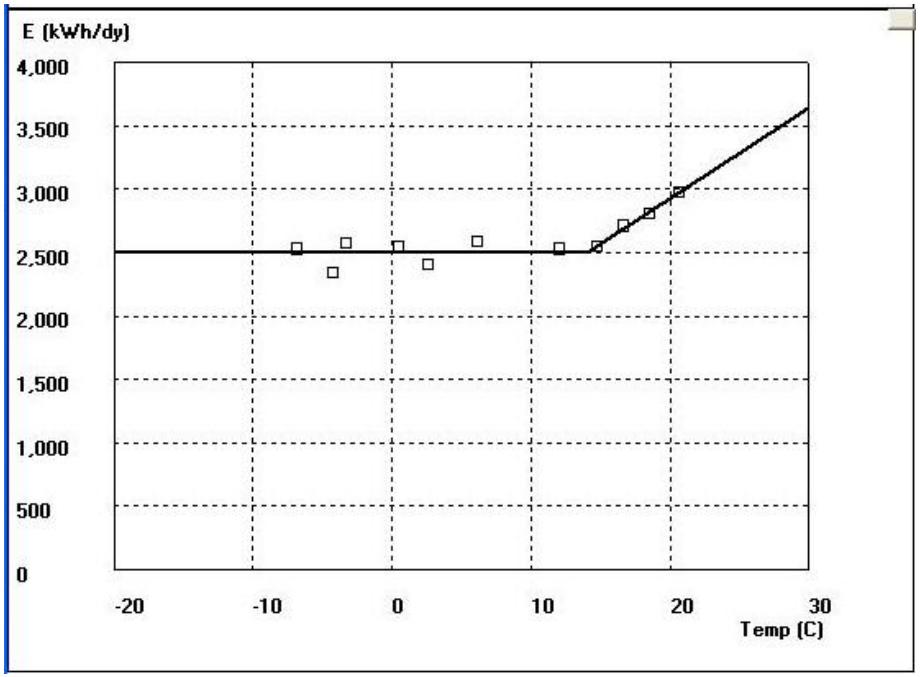
1) the monthly time scale
2) outdoor air temperature as sole independent variable?

Two sources of error:

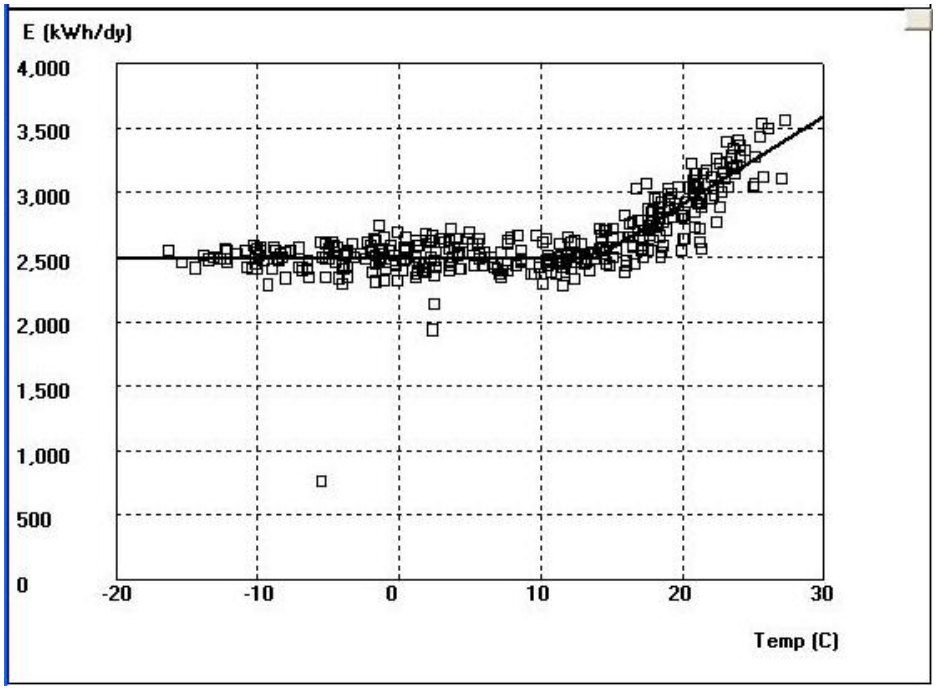
- Time-scale error from using monthly data
- Phase-shift error when environmental drivers are out of phase with temperature

Time-scale Error

Grocery Store Electricity Use



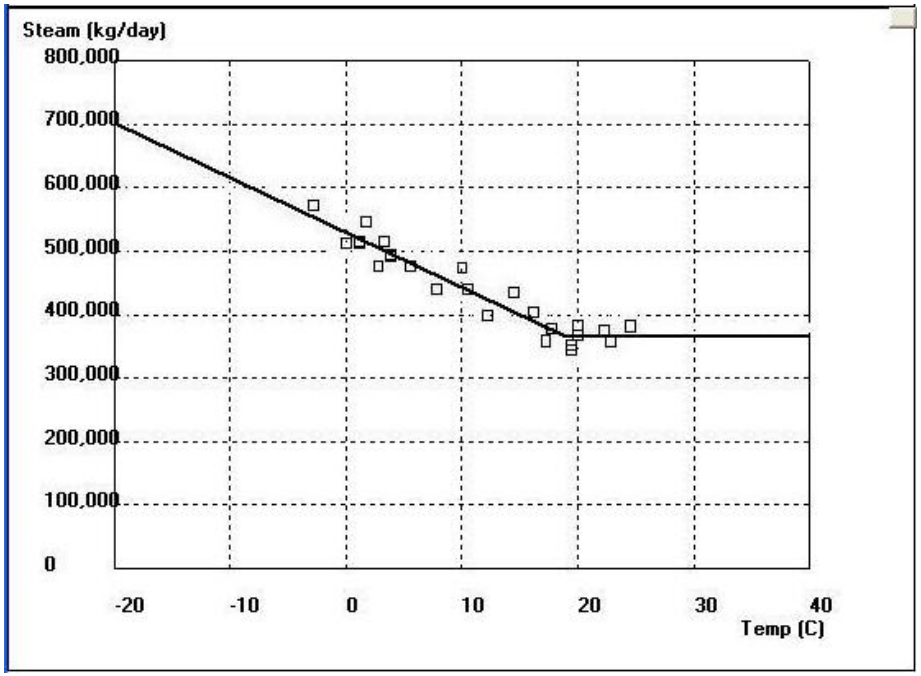
Monthly Regression
$R^2 = 0.89$



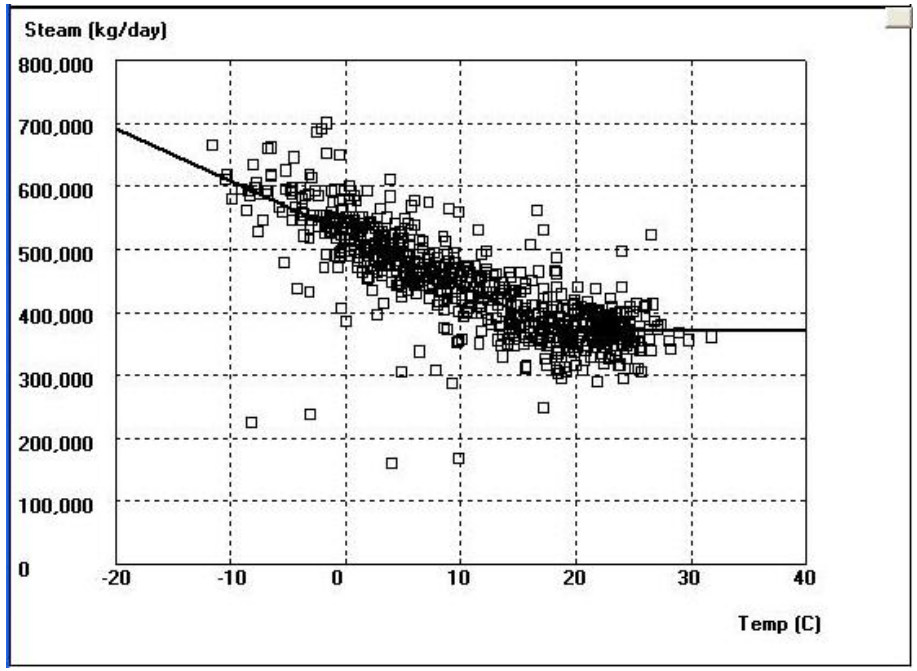
Daily Regression
$R^2 = 0.69$

Time-scale Error

Plastics Manufacturing Plant Steam Use



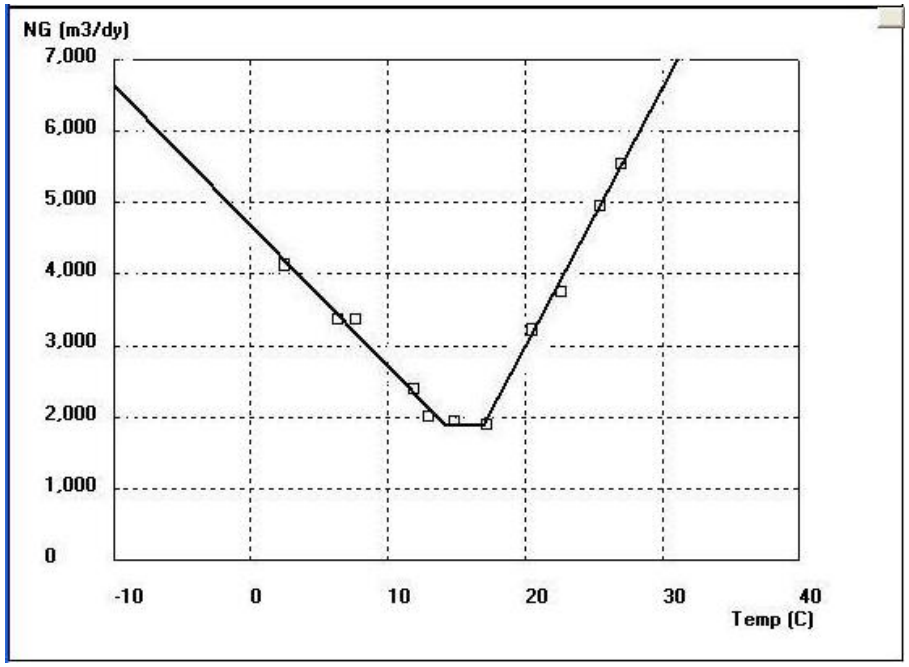
Monthly Regression
$R^2 = 0.93$



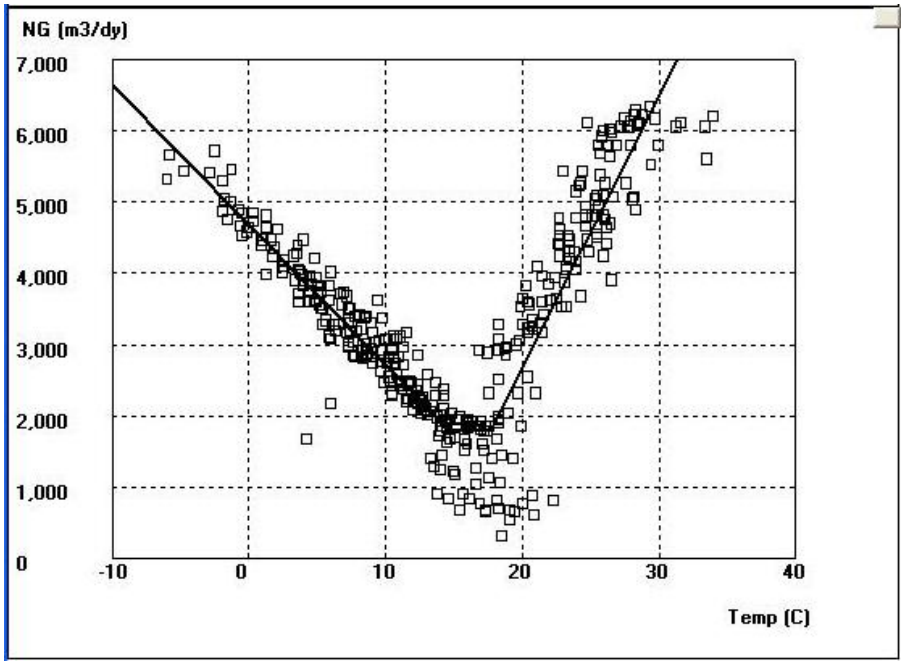
Daily Regression
$R^2 = 0.66$

Time-scale Error

High-Rise Apartment Building Fuel Energy



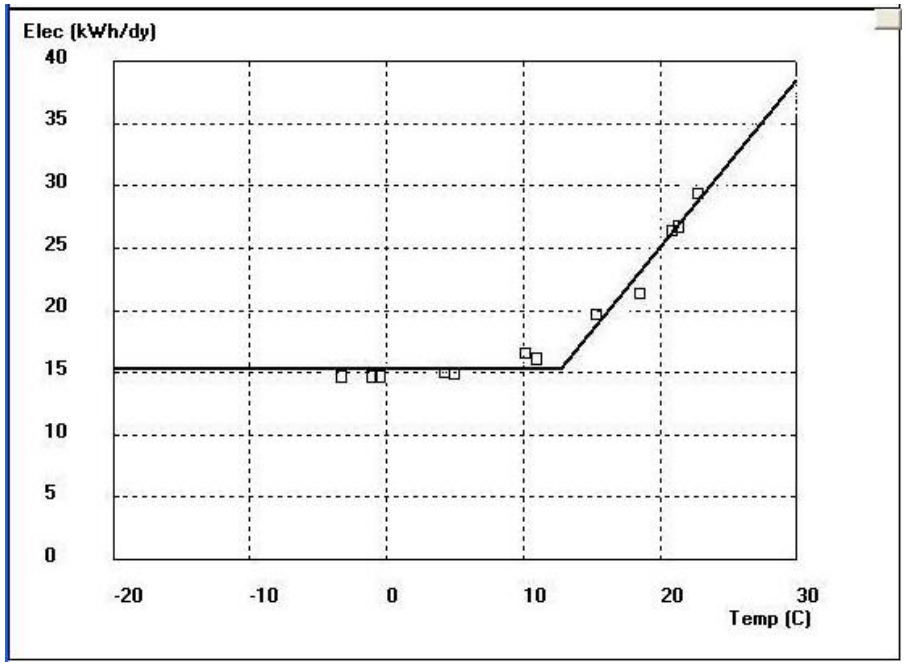
Monthly Regression
$R^2 = 0.99$

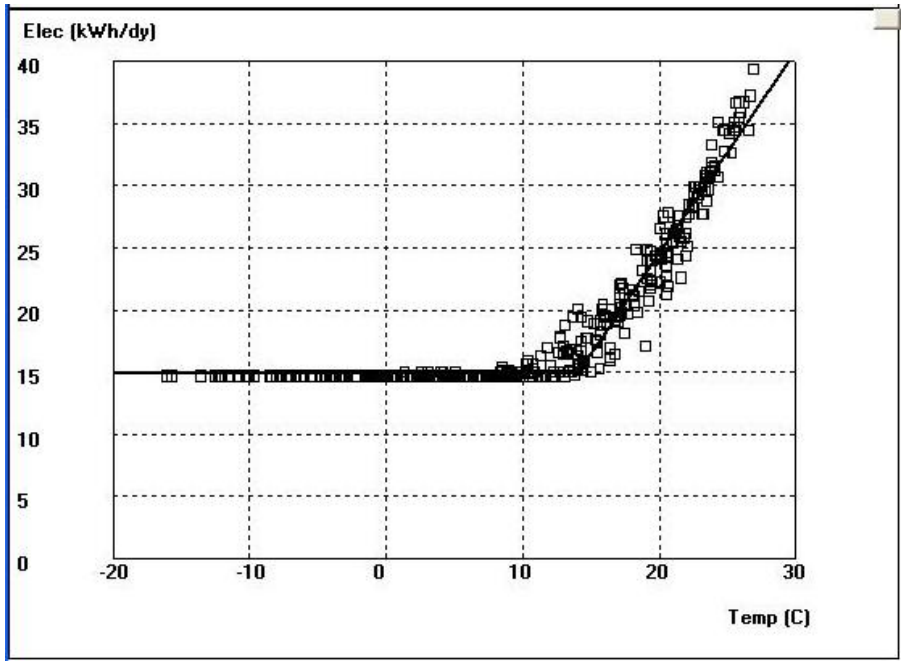


Daily Regression
$R^2 = 0.82$

Time-scale Error

Simulated Residential Electricity Use



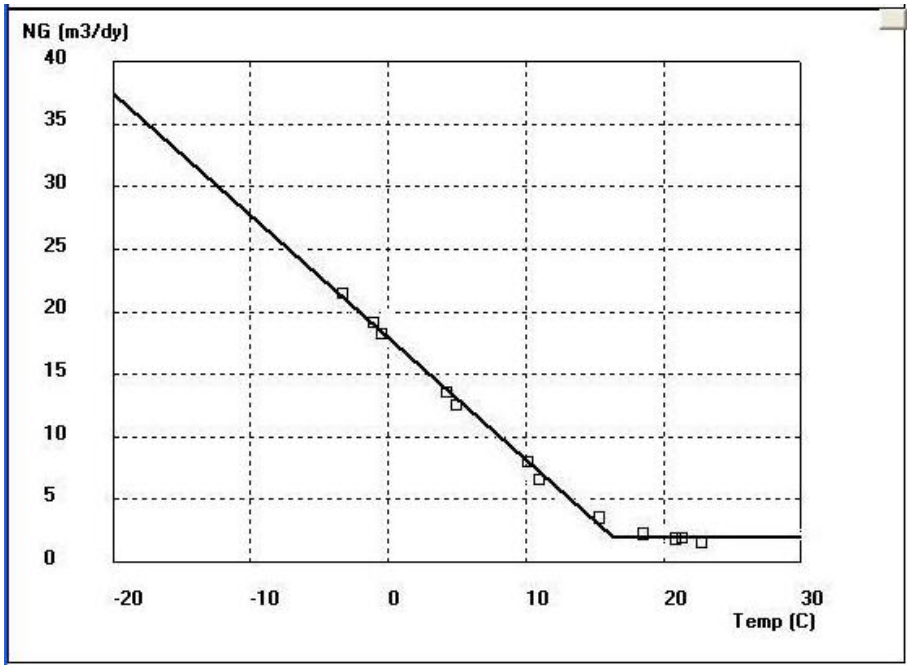


Monthly Regression
$R^2 = 0.98$

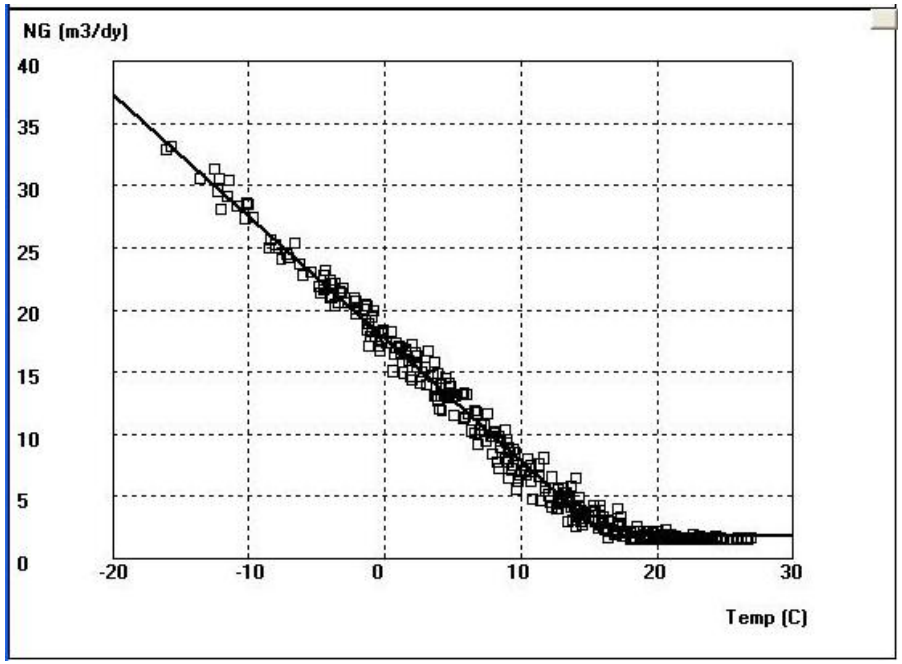
Daily Regression
$R^2 = 0.96$

Time-scale Error

Simulated Residential Fuel Use



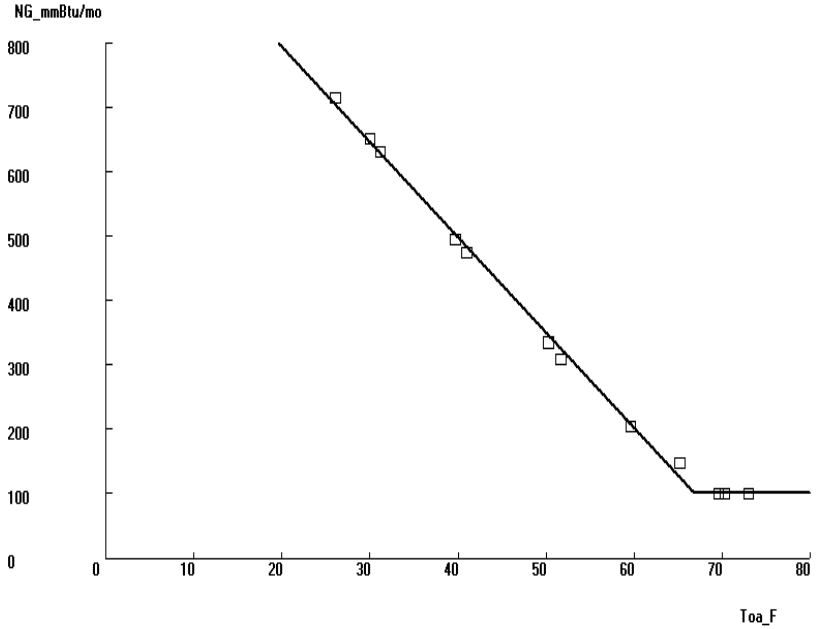
Monthly Regression
$R^2 = 1.00$



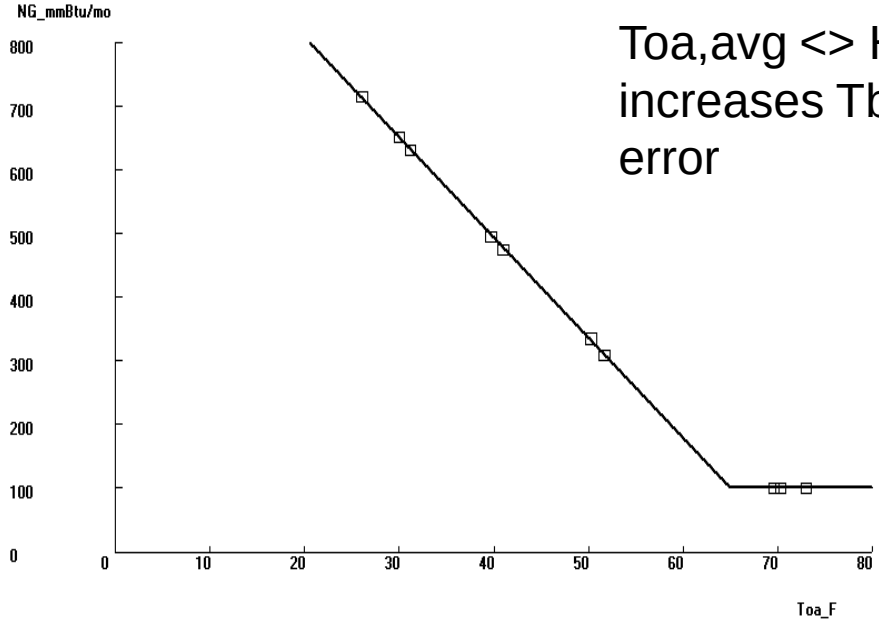
Daily Regression
$R^2 = 0.99$

But We Do Have Some Time-scale Error

Simulated Industrial Facility Fuel Use



12 Month Regression
Deviation from Actual
Fi: ± 0.1%
HS: ± 5.7%
Tb: ± 2.8 F



Toa,avg <> HDD increases Tb error

Regression With May/Sept Removed
Deviation from Actual
Fi: ± 0.1%
HS: ± 0.4%
Tb: ± 0.9 F

Time-scale Error: Summary

- Using monthly data does not significantly decrease ability to derive building parameters.

- Most significant error is in Tb.

Toa as Sole Independent Variable?

- Primary environmental drivers are:
  - Outdoor air temperature (Toa)
  - Solar radiation (S)
  - Humidity (H)
  - Wind speed (infiltration) (W)
- But all linearly correlated with outdoor air temperature
  - Solar radiation increases with outdoor air temperature
  - Humidity increases with outdoor air temperature
  - Wind speed decreases with outdoor air temperature
- Thus, Toa is a surrogate variable for all primary environmental drivers, and it follows that
  - Adding solar, humidity and wind speed as additional independent variables only marginally improves fit
  - Standard error on coefficients is so large that usefulness for prediction is questionable

But We Do Have 'Phase-shift' Error

- Ground losses lag Toa by 1-2 months
- Domestic hot water energy use lags Toa by 1-3 months
  - Outdoor air temperature (Toa)
  - Solar radiation (S)
  - Humidity (H)
  - Wind speed (infiltration) (W)
- But all linearly correlated with outdoor air temperature
  - Solar radiation increases with outdoor air temperature
  - Humidity increases with outdoor air temperature
  - Wind speed decreases with outdoor air temperature
- Thus, Toa is a surrogate variable for all primary environmental drivers, and it follows that
  - Adding solar, humidity and wind speed as additional independent variables only marginally improves fit
  - Standard error on coefficients is so large that usefulness for prediction is questionable

Error Summary

- Inverse models of monthly energy versus outdoor air temperature are:

  1. remarkably robust
  2. provide good estimates of building parameters

- However, there is some

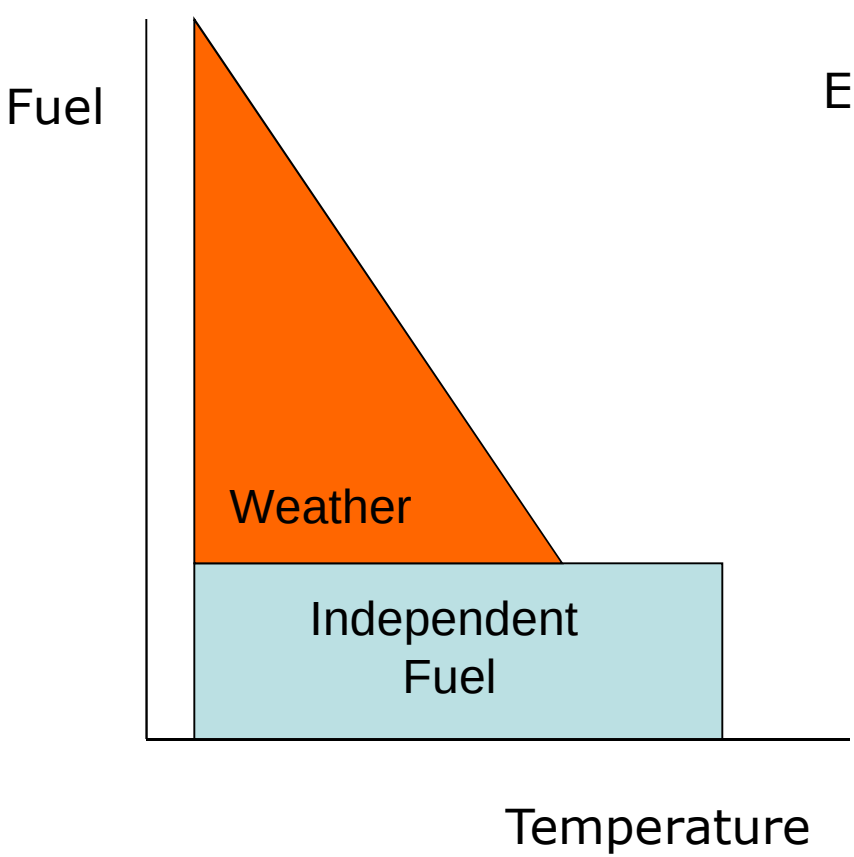
  1. time-scale error
  2. phase-shift error

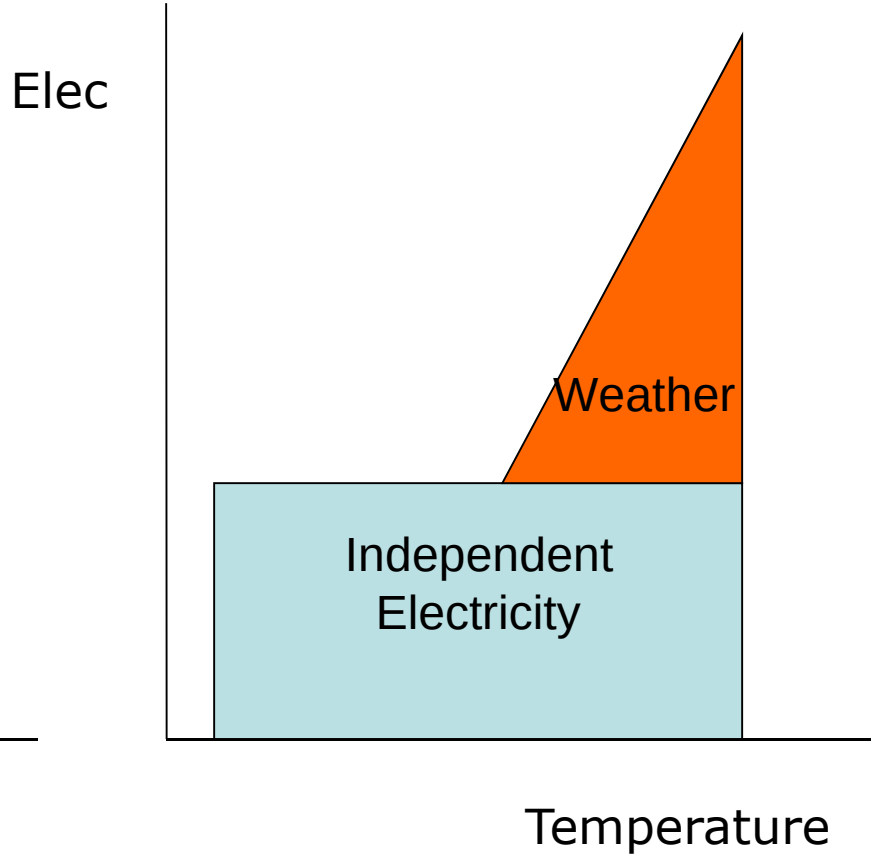
  inherent in the inverse modeling approach that reduces the precision with which the parameters are known.

How to use Inverse Modeling for Calibration?

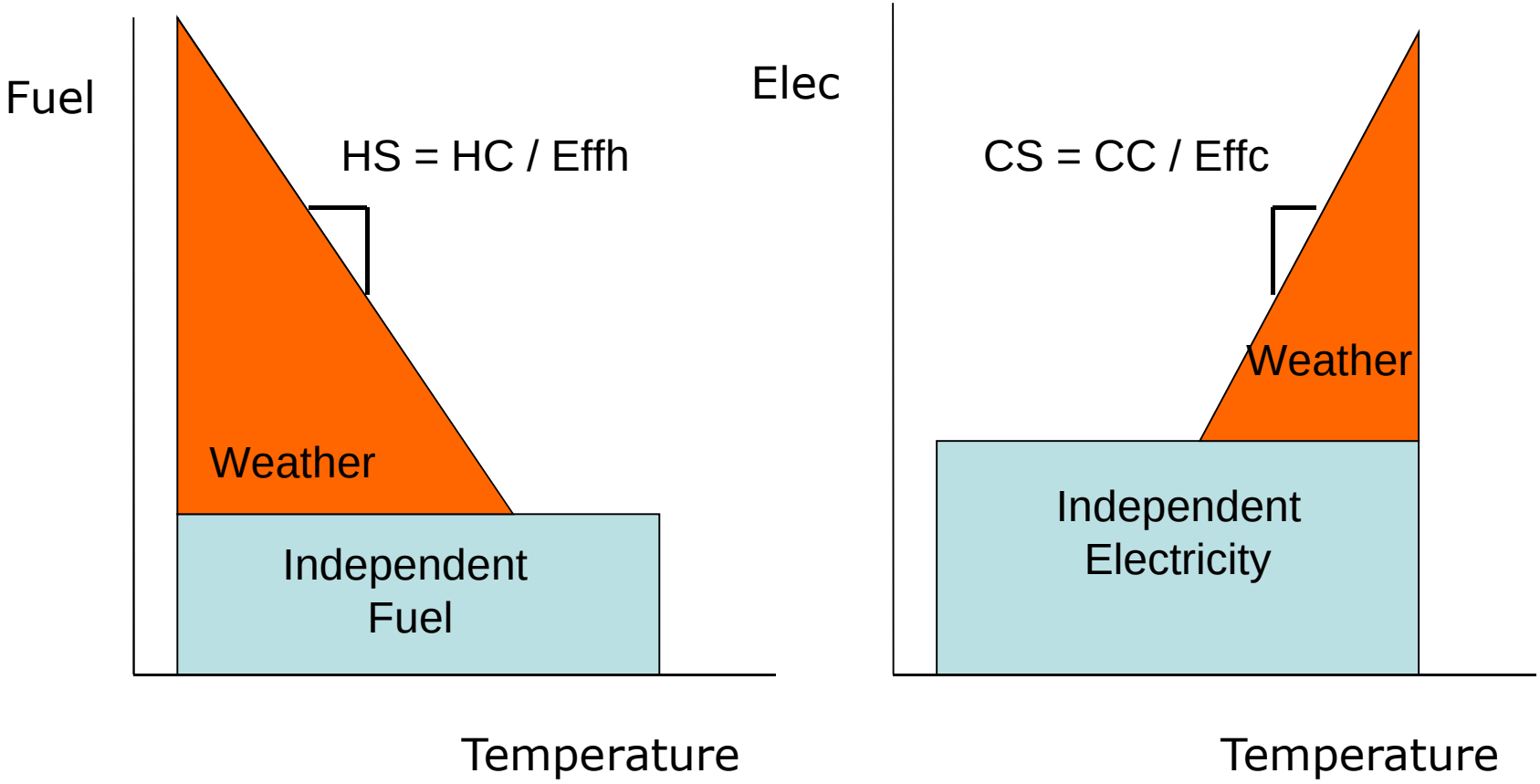
- Inverse modeling improves understanding about what is happening in the building

Disaggregate Fuel and Electricity Use

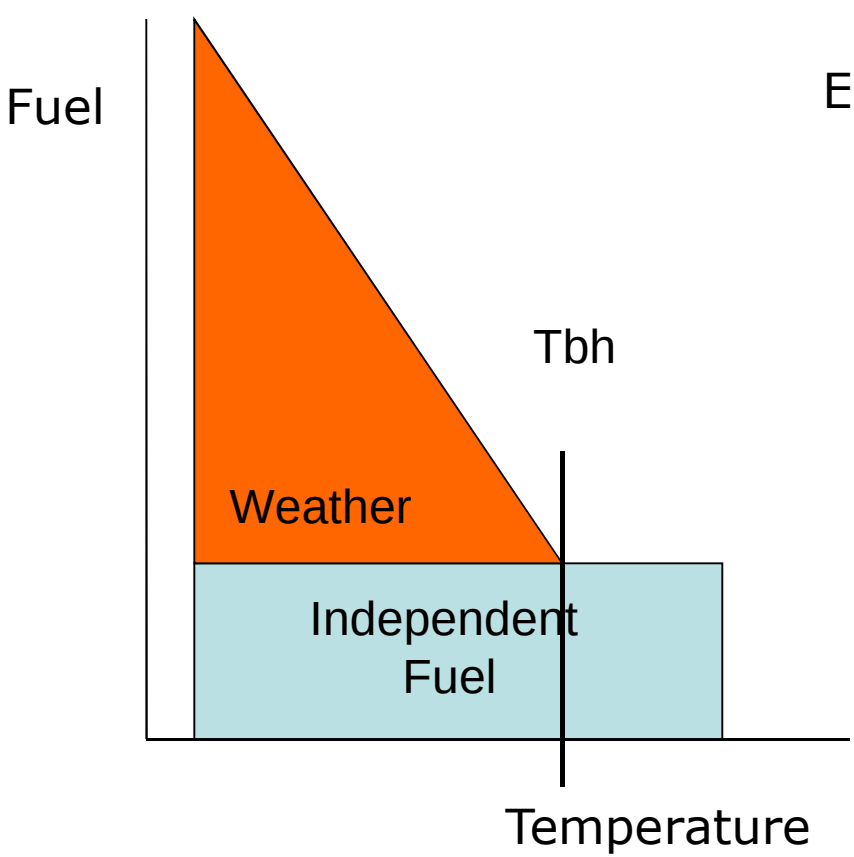


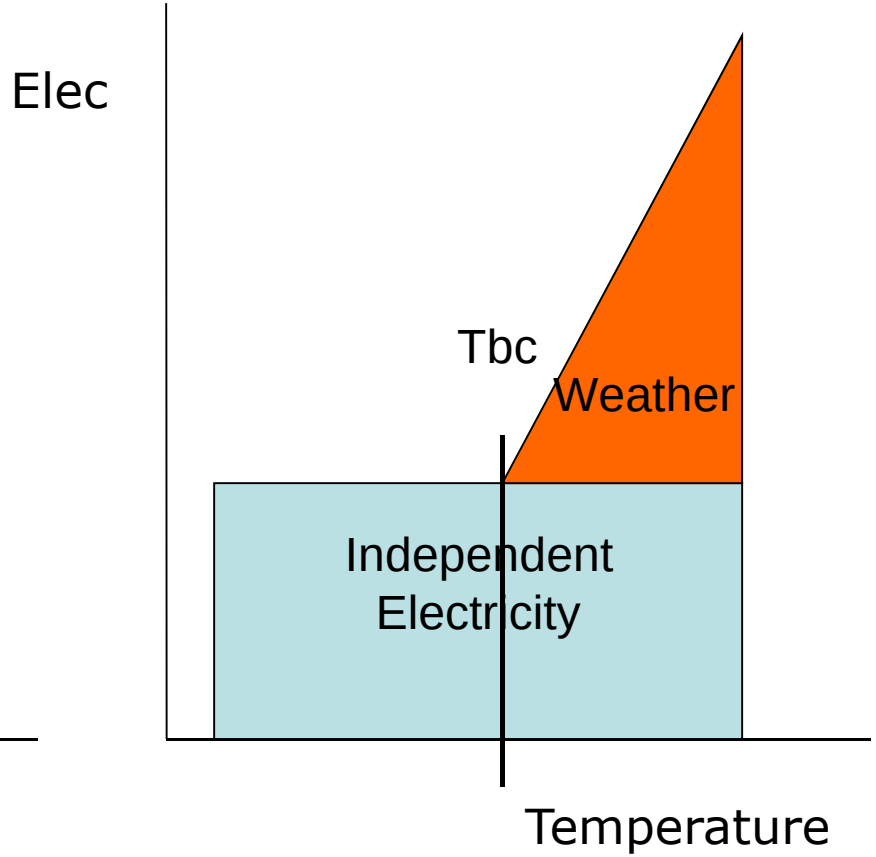


Determines HS and CS



Determines Tbal

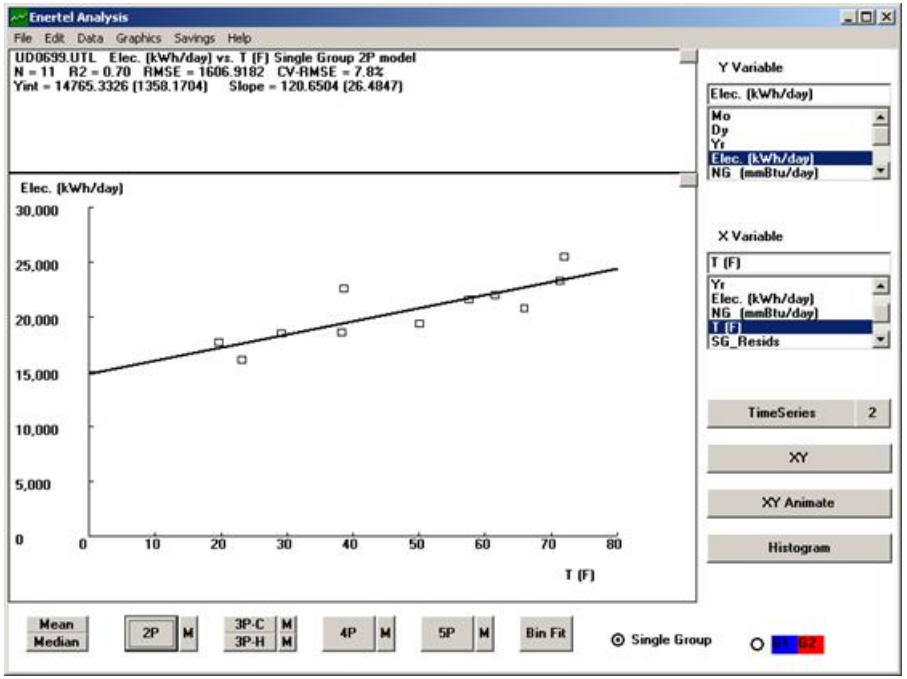




In Summary, Inverse Modeling Identifies

- Space heating and cooling energy use
- Independent energy use
- HS = (UA + V p cp) / Effh
- CS = (UA + V p cp) / Effc
- Tb = Ts – Qint / HC

Using Models to Identify Operational Issues: Economizer Failure

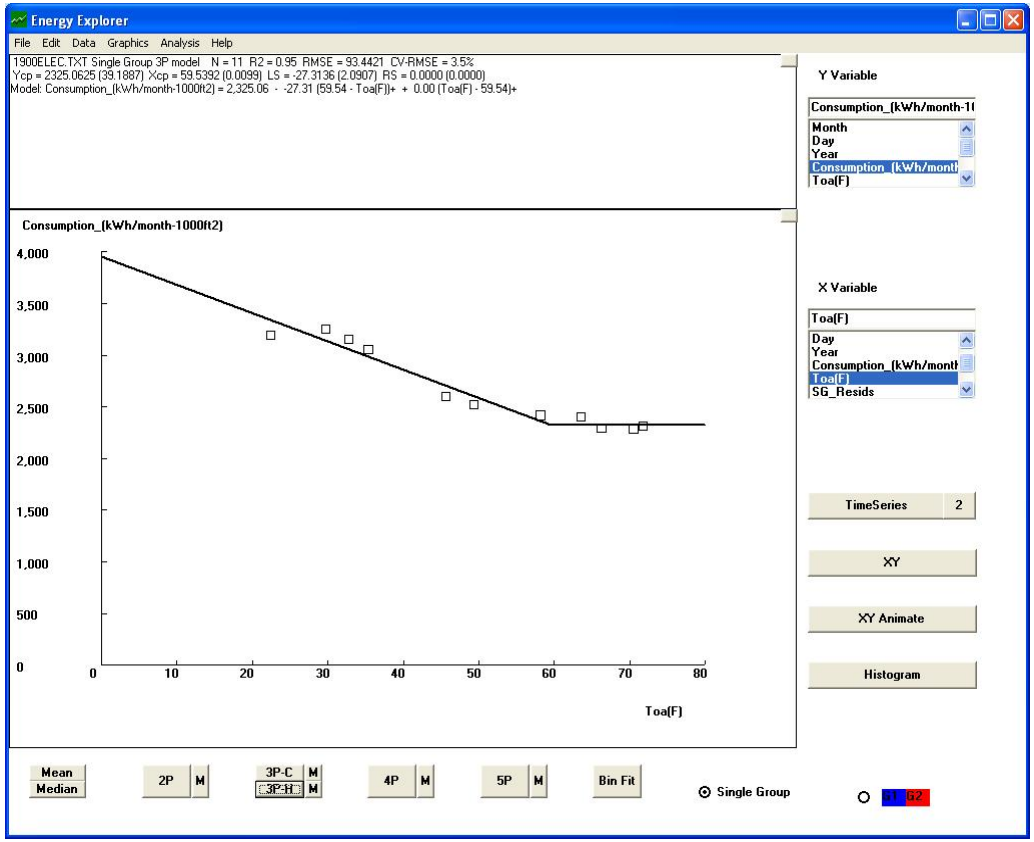


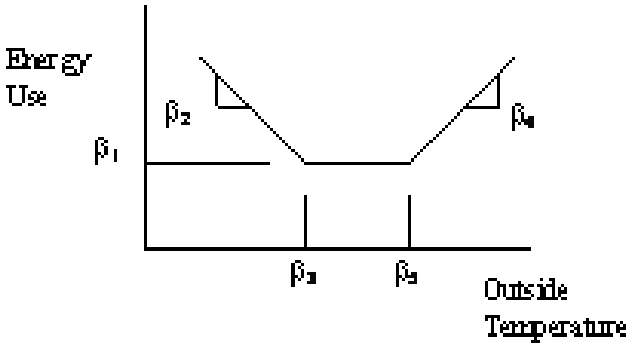
Cooling slope should flatten at low temps

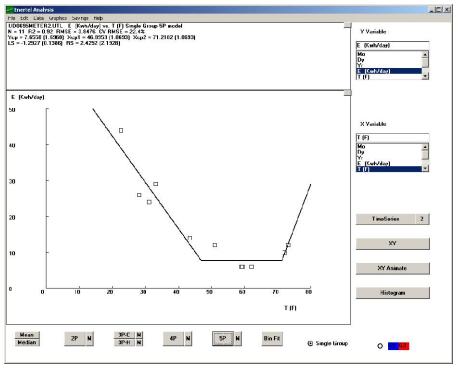
Broken and missing outdoor air damper gears

Using Models to Identify Operational Issues: Unexpected Shape

All electric building with large solar/envelope gain

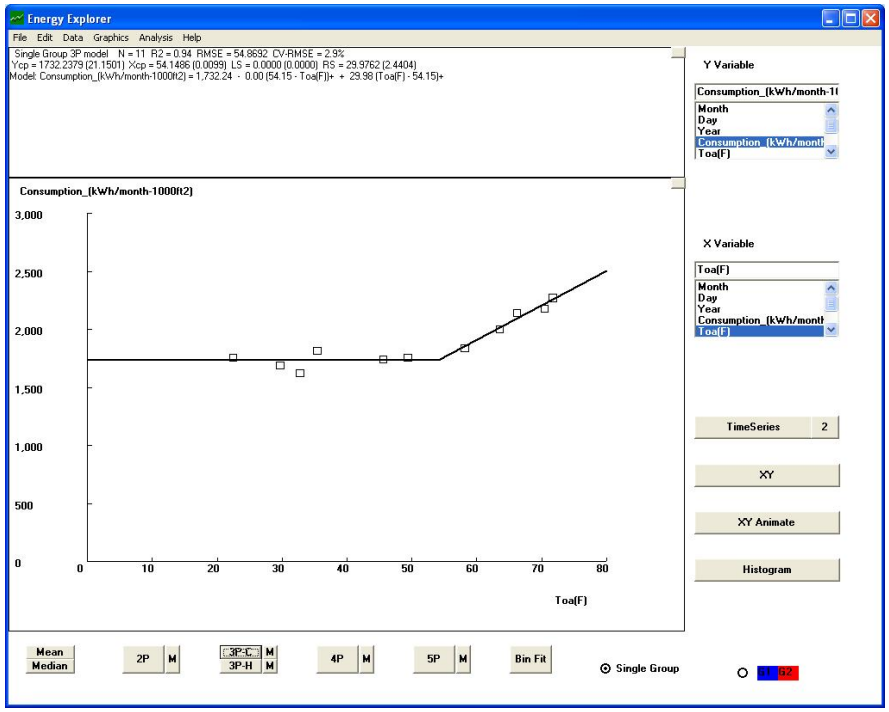


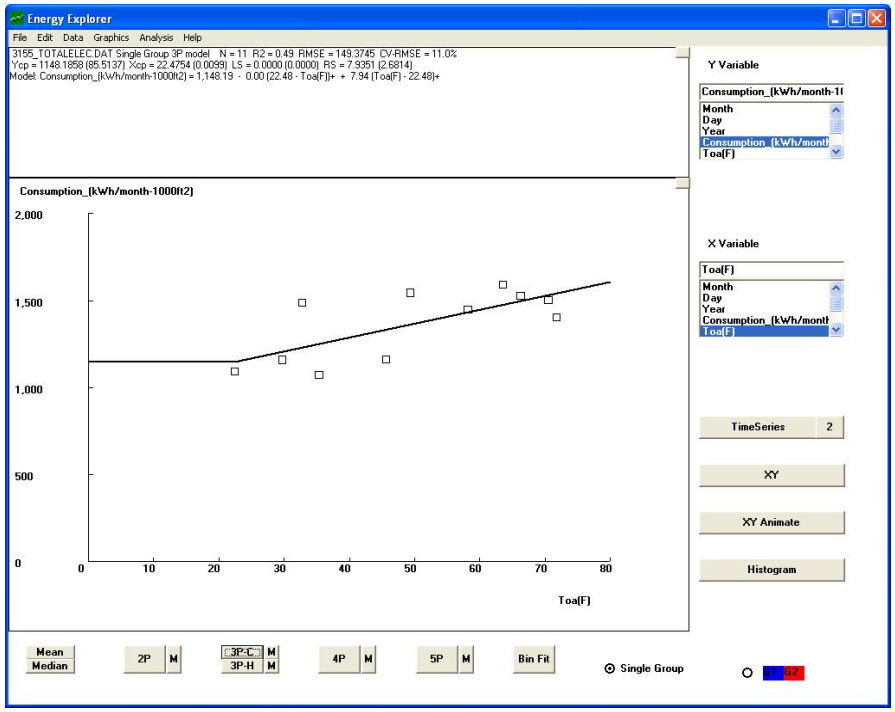




Using Models to Identify Problems: High Scatter = Poor Control

Nearly identical buildings with different control/hvac systems

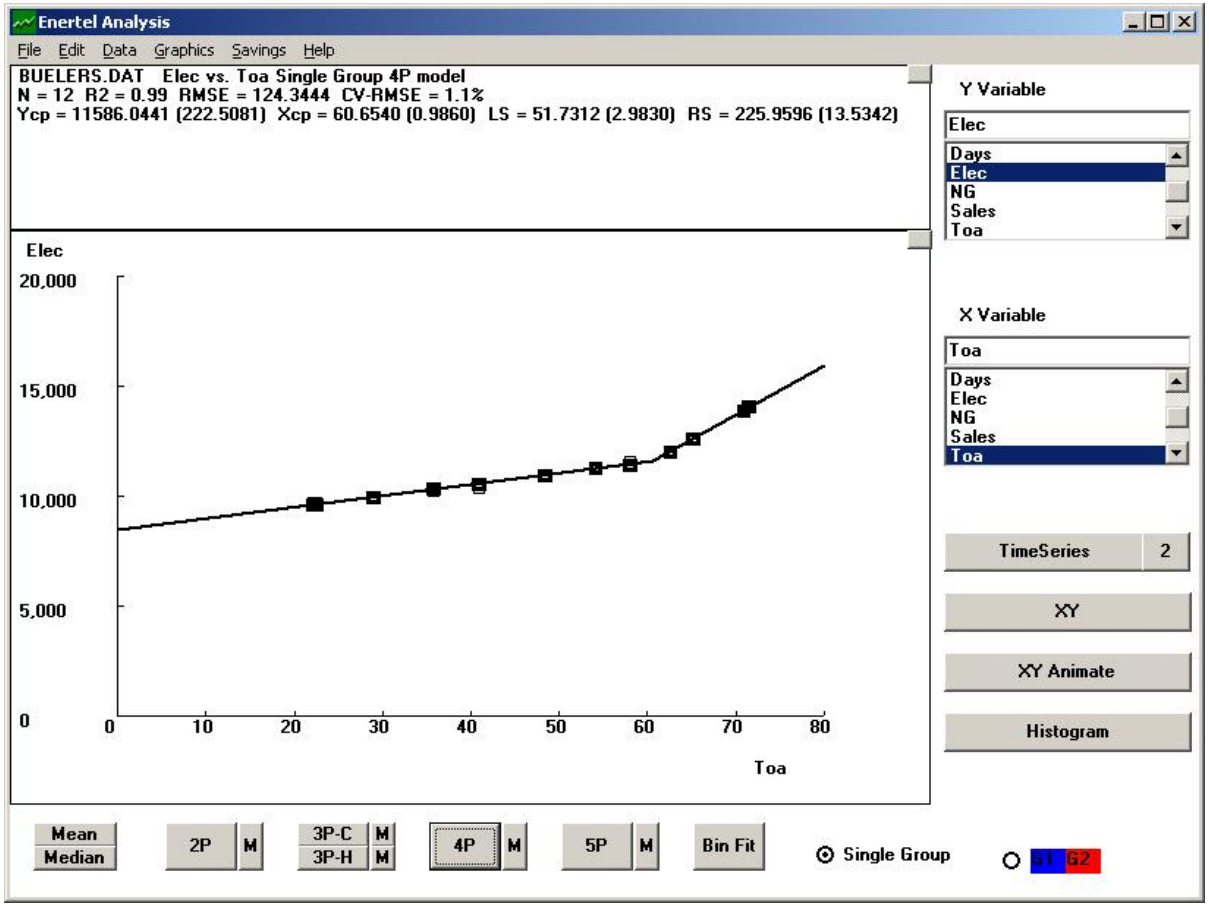




$R^2 = 0.94$

$R^2 = 0.49$

Using Models to Identify Dual Temperature Dependence



R^2 = 0.99 CV-RMSE = 1.1%

Thank you!