Model-Based Thermal Load Estimation in Buildings

Zheng O'Neill

Satish Narayanan

Rohini Brahme

United Technologies Research Center

East Hartford, CT

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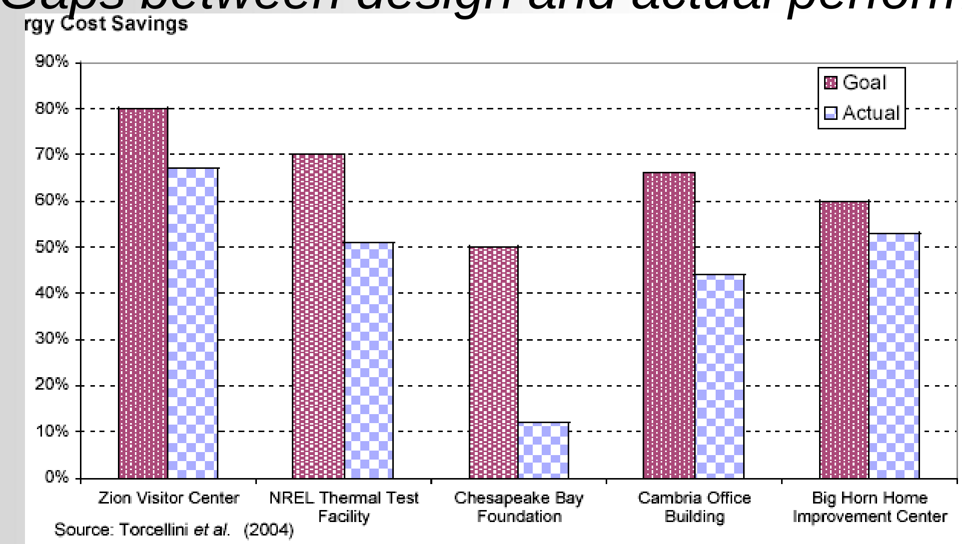
Outline

- Problem Statement
- Objectives
- Estimation Methodology
- Results:
  - Internal zone
  - External zone
  - Multi-scale
- Verification of Methodology
- Conclusions

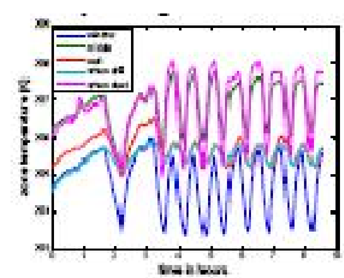
Problem Statement

- Buildings account for nearly 40% of global energy consumption
- Operational faults waste ~10-20% energy*
- Energy waste and faults in buildings NOT visible
  - Unmeasured quantities
    - Lighting/plug loads (could be measured, but cost is an issue)
    - Occupancy, Infiltration, etc.
  - Require model-based estimation with real time data
    - Enable cost-effective monitoring and diagnosis

Gaps between design and actual performance



Façade Damage



Cycling Controls

Improper lighting schedules

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* TIAX report (2005)

Most of these faults are invisible

Objectives

- Develop techniques to estimate parameters for reduced order building models with time-varying inputs from a BMS database.
- Estimate the internal loads (e.g. lighting, equipment, people) profile to:
  - Understand building energy usage
    - Abnormal loads → improperly implemented schedules (e.g. lights on when unoccupied)
      - Abnormal loads → isolate zones → correlate zonal loads with energy usage (sub-metered) → correlate abnormal loads with operational problems or faults that result in energy performance degradation
  - Help refine the input load profile to energy simulation programs: enabling real-time whole building energy simulation that could be visualized along with metered performance

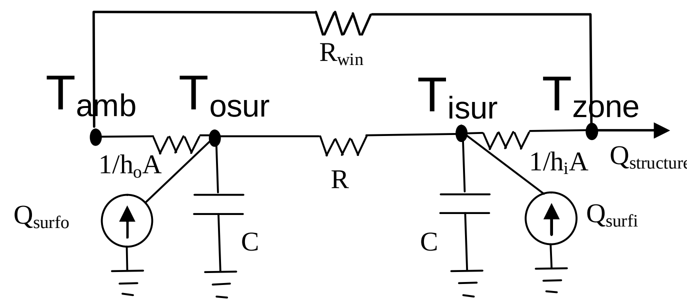
Estimation Methodology

BMS data

Reference Model

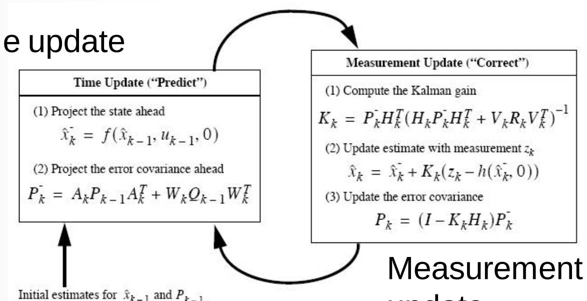
Recast

Dynamic Reduced Order Model



Extended Kalman Filter Based Estimator

Time update



Measurement update

- Understand the system to be modeled
- Understand the BMS data
- Understand the key parameters to help establish assumptions in the equation based dynamic model

ACH; Solar gains; Internal load
Unmeasured zonal conditions (T, RH)

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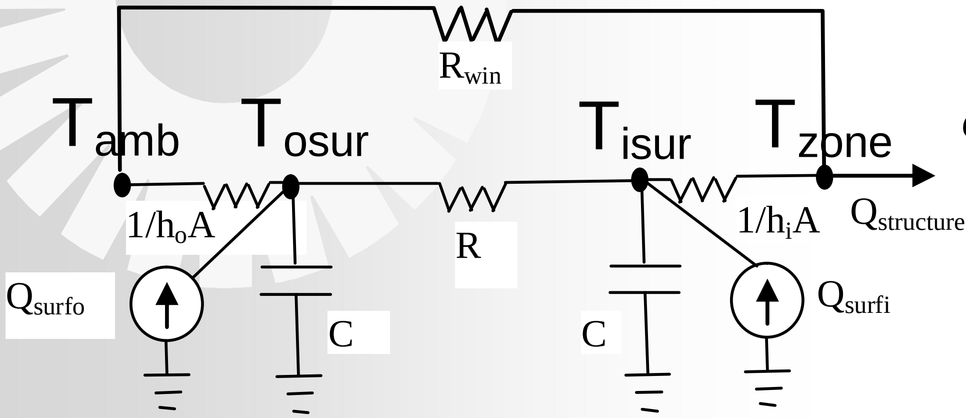
Building Model

Thermal network model (envelope)



$$C\frac{dT_{osurf}}{dt} = h_o A\left(T_{amb} - T_{osurf}\right) + \frac{T_{isurf} - T_{osurf}}{R} + Q_{surfo}$$

$$C\frac{dT_{isurf}}{dt} = h_i A\left(T_{zone} - T_{isurf}\right) + \frac{T_{osurf} - T_{isurf}}{R} + Q_{surfi}$$

$$Q_{structure} = h_i A(T_{isuf} - T_{zone}) + \frac{(T_{amb} - T_{zone})}{R_{win}}$$

$$R = \frac{l}{kA} \qquad C = \frac{\rho C_p l A}{2}$$

Energy Balance

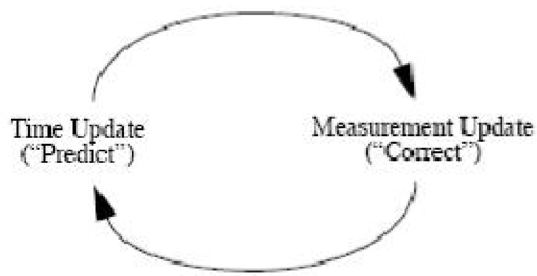
Lump loads from lighting, people, and equipment

$$m_{air\_zone}\left(C_{pa} + \omega_{zone} C_{pv}\right)\frac{dT_{zone}}{dt}$$
$$= \dot{m}_{air\_sa} C_{pa}\left(T_{sa} - T_{zone}\right) + \dot{m}_{air\_sa} C_{pv}\left(\omega_{sa} T_{sa} - \omega_{zone} T_{zone}\right) + Q_{int}$$
$$+ \sum_{i}^{N_{surface}} Q_{structure\_i} + \dot{m}_{\inf} C_{pa}\left(T_{oa} - T_{zone}\right) + \sum_{i=1}^{N_{zone}} \dot{m}_i C_{pa}\left(T_{zonei} - T_{zone}\right) + \dot{m}_v C_{pv} T_{zone}$$

Mass Balance (water vapor)

$$m_{air\_zone}\frac{d\omega_{zone}}{dt} = \dot{m}_{air\_sa}\left(\omega_{sa} - \omega_{zone}\right) + \dot{m}_v$$

Extended Kalman Filter (EKF)

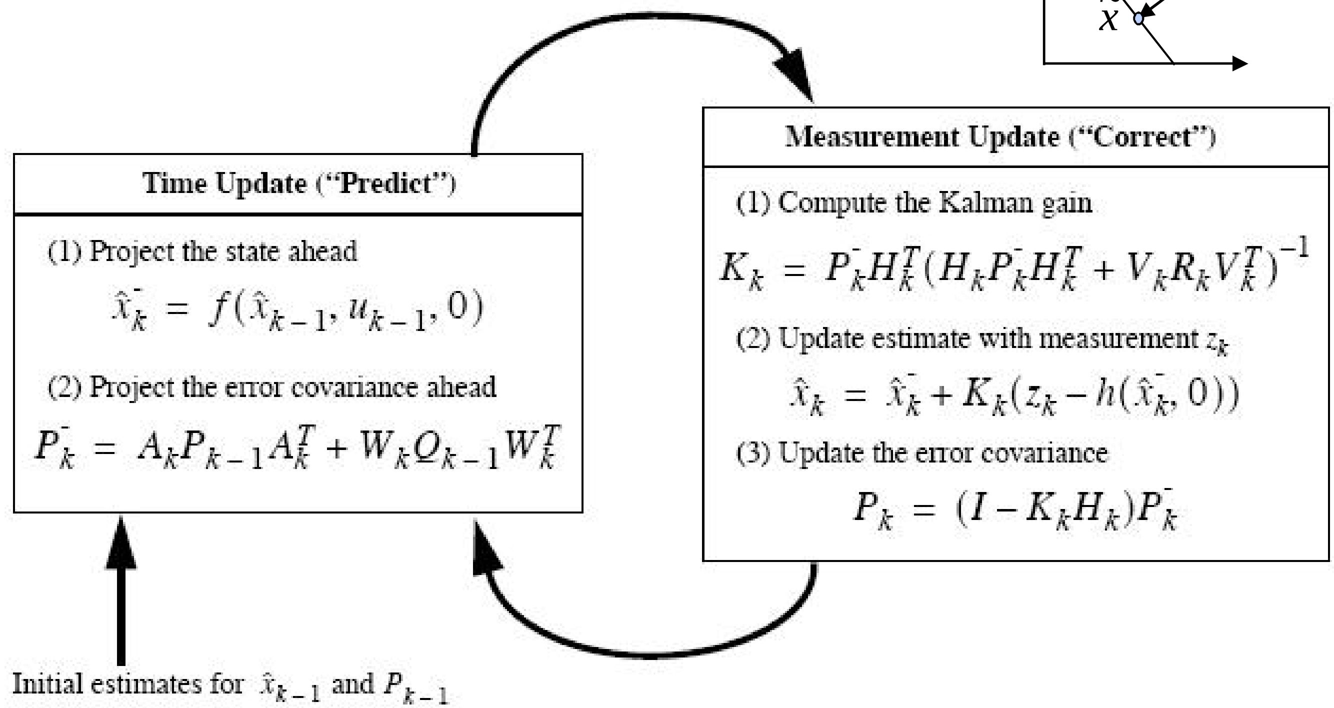


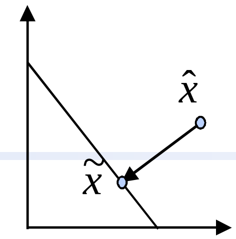
Non linear difference equation

$$x_k = f(x_{k-1}, u_{k-1}, w_{k-1})$$

Measurement

$$z_k = h(x_k, v_k)$$

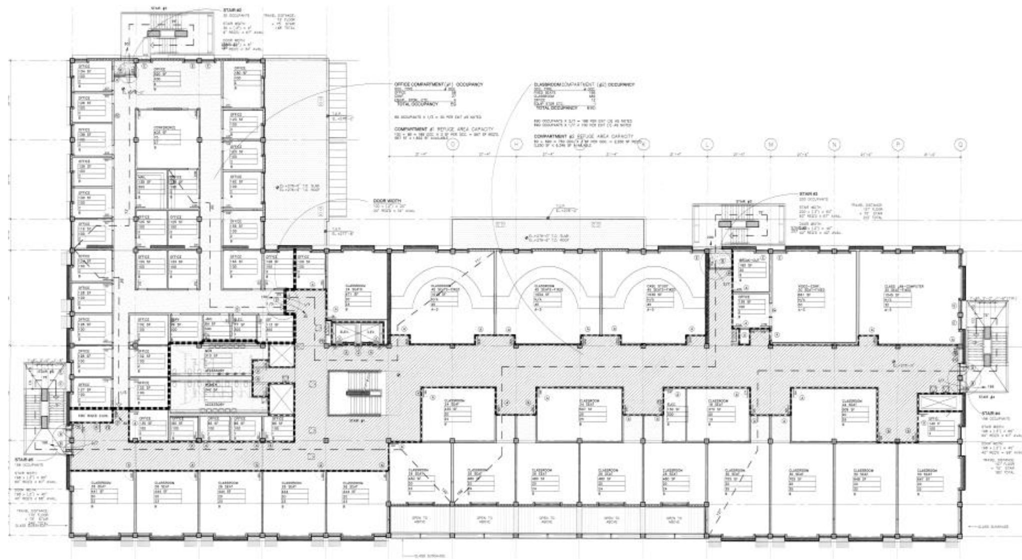




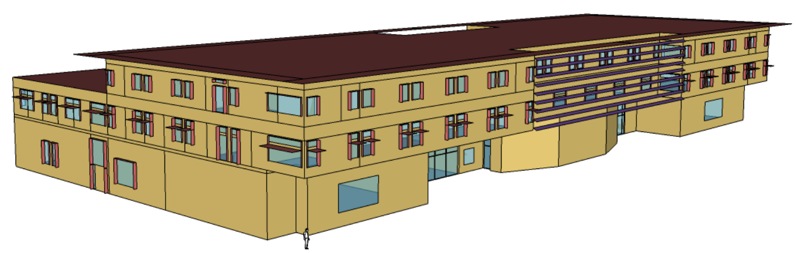
- The time update projects the current state estimate ahead in time. The measurement update adjusts the projected estimate by an actual measurement at that time
- State space form and recursive: predict, correct, predict…
- Implementation with constraints: Directly project an unconstrained state on to a constrained surface – a ***quadratic programming problem***

UC Merced Classroom and Office Building

- Classroom and office building
  - 3 stories, 92,000 ft^2
  - California climate zone 12
  - Dual duct dual fan variable air volume AHU
  - Dual duct VAV box at zone level
  - Central plant provides heating and cooling

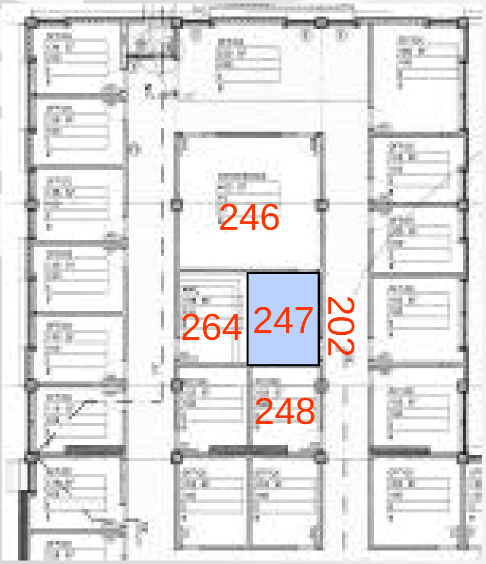


2nd Floor Plan

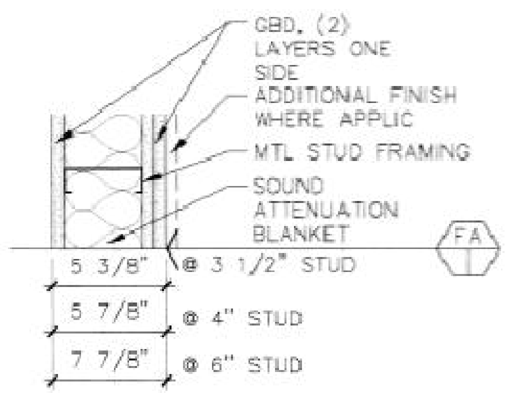


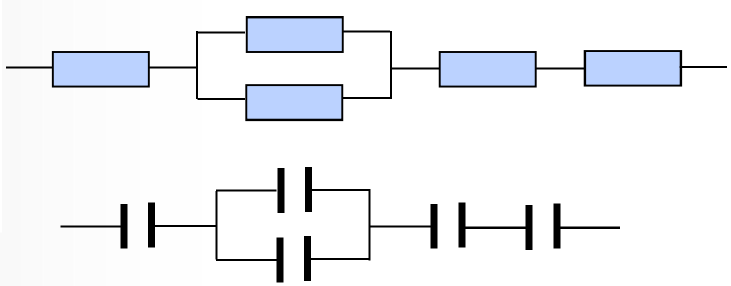
EnergyPlus Rendered Geometry

Internal Zone (DDV-247)



- Office on 2nd floor
- Only considered sensible heat transfer
- Adiabatic floor and roof
- No surface heat flux due to solar radiation
- Dynamic data available:
  - Zone temperatures
  - VAV box supply air flow rate
  - VAV box supply air temperature
    = AHU CD supply air temperature +5C
    - *From the additional HOBO sensor data*
- Static data available:
  - Interior wall material and configuration
  - Room geometry (3.25m*3.86m*3.96m)





Rw=Re=0.25024 W/K

Rn=Rs=0.2972 W/K

Cw=Ce=12506.83 J/K

Cs=Cn=1053.36 J/K

State Space Formulation – Internal Zones (DDV247)

$$\dot{X} = f(x,u)$$
$$Y = CX$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Input vector: $U = \begin{bmatrix} u_1 & u_2 & u_3 & u_4 & u_5 & u_6 \end{bmatrix} = \begin{bmatrix} \dot{m}_{sa} & T_{sa} & T_w & T_n & T_e & T_s \end{bmatrix}$

History of zone temperature from sensor: $y = T_{247}(t) = T_R(t)$

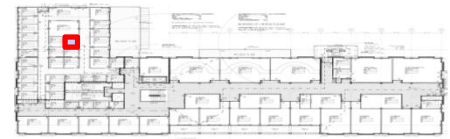
$$\dot{X} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \\ \dot{x}_3 \\ \dot{x}_4 \\ \dot{x}_5 \\ \dot{x}_6 \\ \dot{x}_7 \\ \dot{x}_8 \\ \dot{x}_9 \\ \dot{x}_{10} \end{bmatrix} = \begin{bmatrix} (-\frac{\dot{m}_{sa}}{m_{air}} - \frac{(h_i A_w + h_i A_n + h_i A_e + h_i A_s)}{m_{air} C_{pa}})x_1 + \frac{h_i A_w}{m_{air} C_{pa}} x_3 + \frac{h_i A_n}{m_{air} C_{pa}} x_5 + \frac{h_i A_e}{m_{air} C_{pa}} x_7 + \frac{h_i A_s}{m_{air} C_{pa}} x_9 + \frac{x_{10}}{m_{air} C_{pa}} + \frac{\dot{m}_{sa} T_{sa}}{m_{air}} \\ -(\frac{h_o A_w}{C_w} + \frac{1}{R_w C_w})x_2 + \frac{1}{R_w C_w} x_3 + \frac{h_o A_w T_w}{C_w} \\ \frac{h_i A_w}{C_w} x_1 + \frac{1}{R_w C_w} x_2 - (\frac{h_i A_w}{C_w} + \frac{1}{R_w C_w})x_3 \\ -(\frac{h_o A_n}{C_n} + \frac{1}{R_n C_n})x_4 + \frac{1}{R_n C_n} x_5 + \frac{h_o A_n T_n}{C_n} \\ \frac{h_i A_n}{C_n} x_1 + \frac{1}{R_n C_n} x_4 - (\frac{h_i A_n}{C_n} + \frac{1}{R_n C_n})x_5 \\ -(\frac{h_o A_e}{C_e} + \frac{1}{R_e C_e})x_6 + \frac{1}{R_e C_e} x_7 + \frac{h_o A_e T_e}{C_e} \\ \frac{h_i A_e}{C_e} x_1 + \frac{1}{R_e C_e} x_6 - (\frac{h_i A_e}{C_e} + \frac{1}{R_e C_e})x_7 \\ -(\frac{h_o A_s}{C_s} + \frac{1}{R_s C_s})x_8 + \frac{1}{R_s C_s} x_9 + \frac{h_o A_s T_s}{C_s} \\ \frac{h_i A_s}{C_s} x_1 + \frac{1}{R_s C_s} x_8 - (\frac{h_i A_s}{C_s} + \frac{1}{R_s C_s})x_9 \\ 0 \end{bmatrix}$$

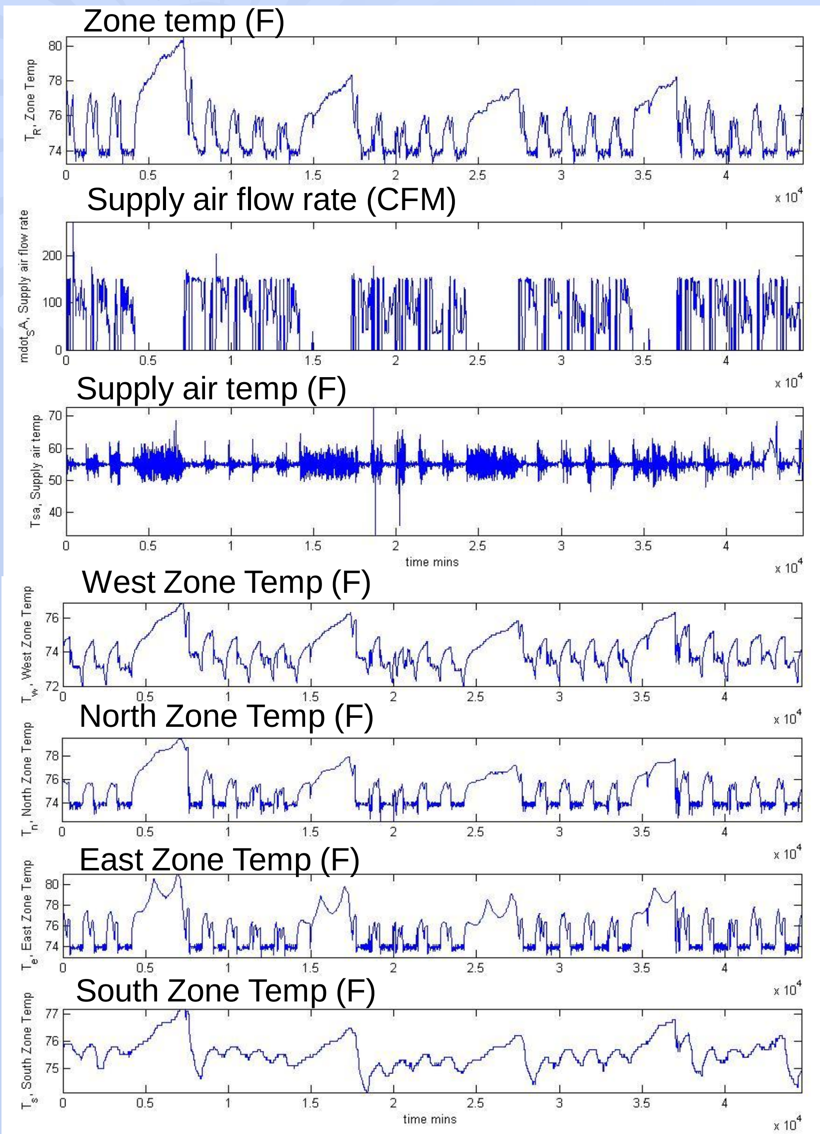
State

$$X = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \\ x_9 \\ x_{10} \end{bmatrix} = \begin{bmatrix} T_{247} \\ T_{ow} \\ T_{iw} \\ T_{on} \\ T_{in} \\ T_{oe} \\ T_{ie} \\ T_{os} \\ T_{is} \\ Q_{\text{int}} \end{bmatrix}$$

Qint includes all internal equipment and light loads (convection part) plus load due to interzone air mixing

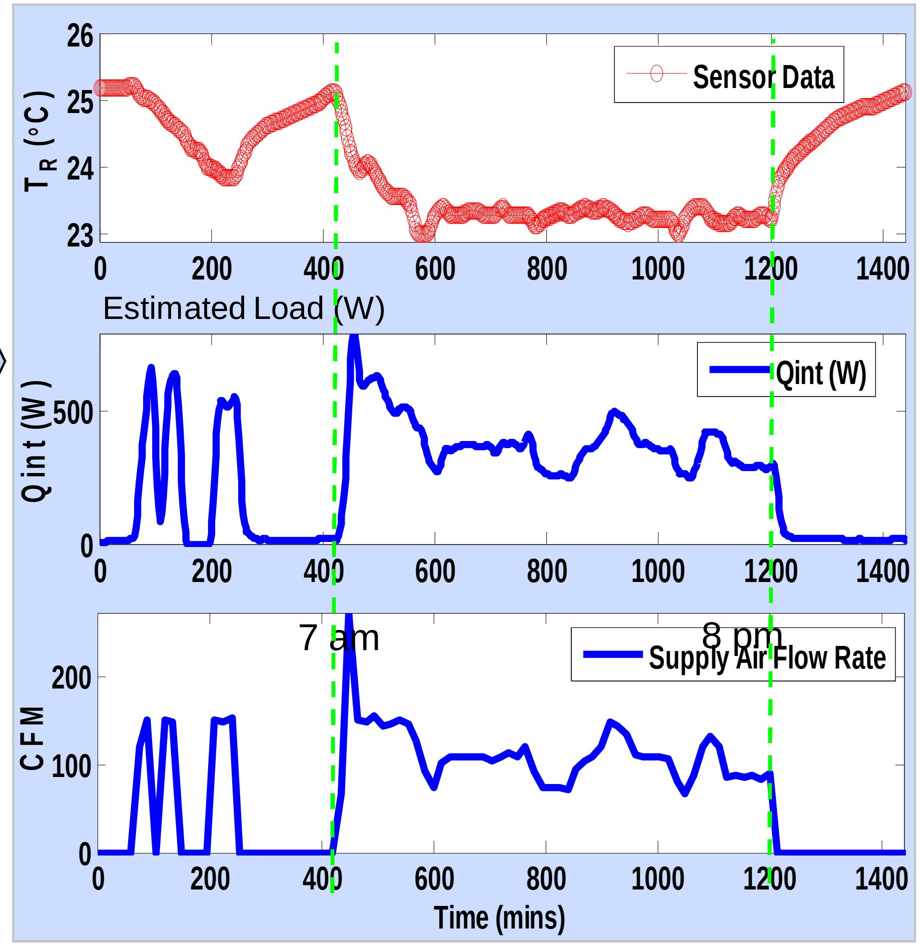
Estimation Results for an Internal Zone DDV247





Post-processed input data (Aug. 2007)

Estimated Results (one day) from EKF



Estimated loads corresponds with measured zone supply air flow rate

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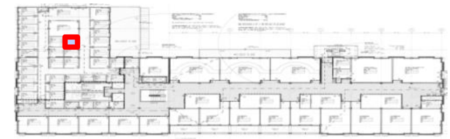
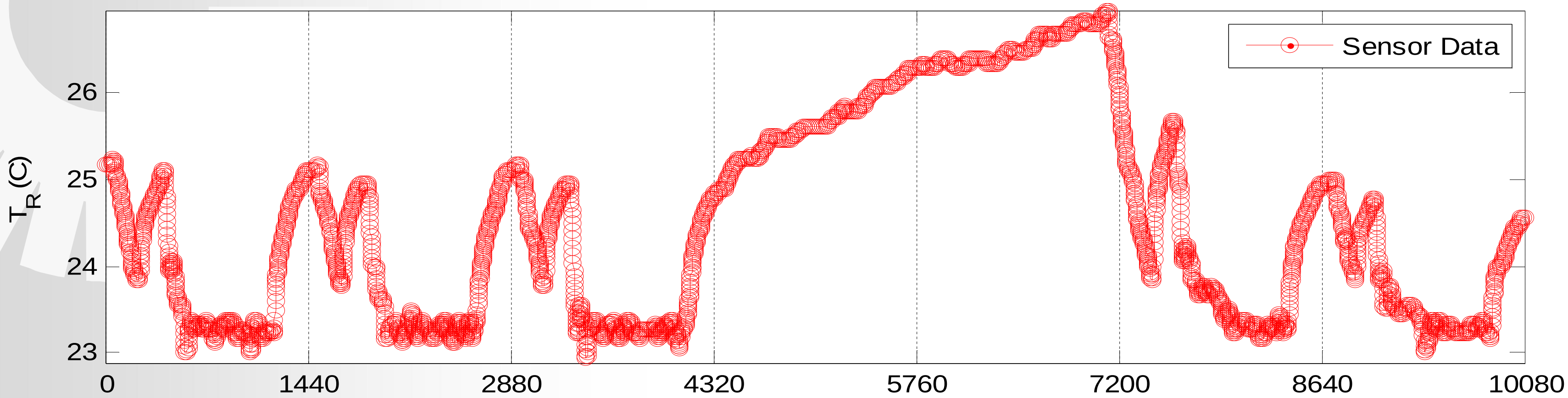
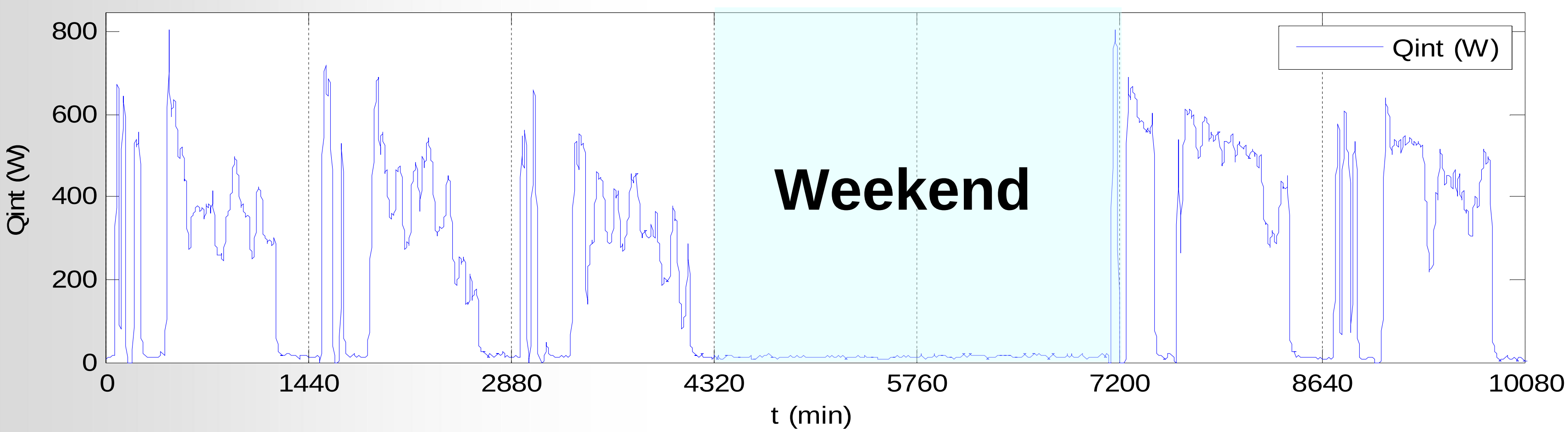
Estimation Results for an Internal Zone DDV247





Estimated load (W)



2 mins Interpolation DDV 247 – Aug 1st to Aug 7th 2007

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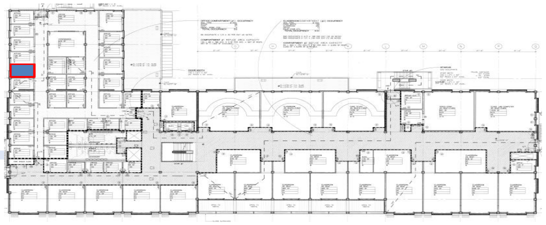
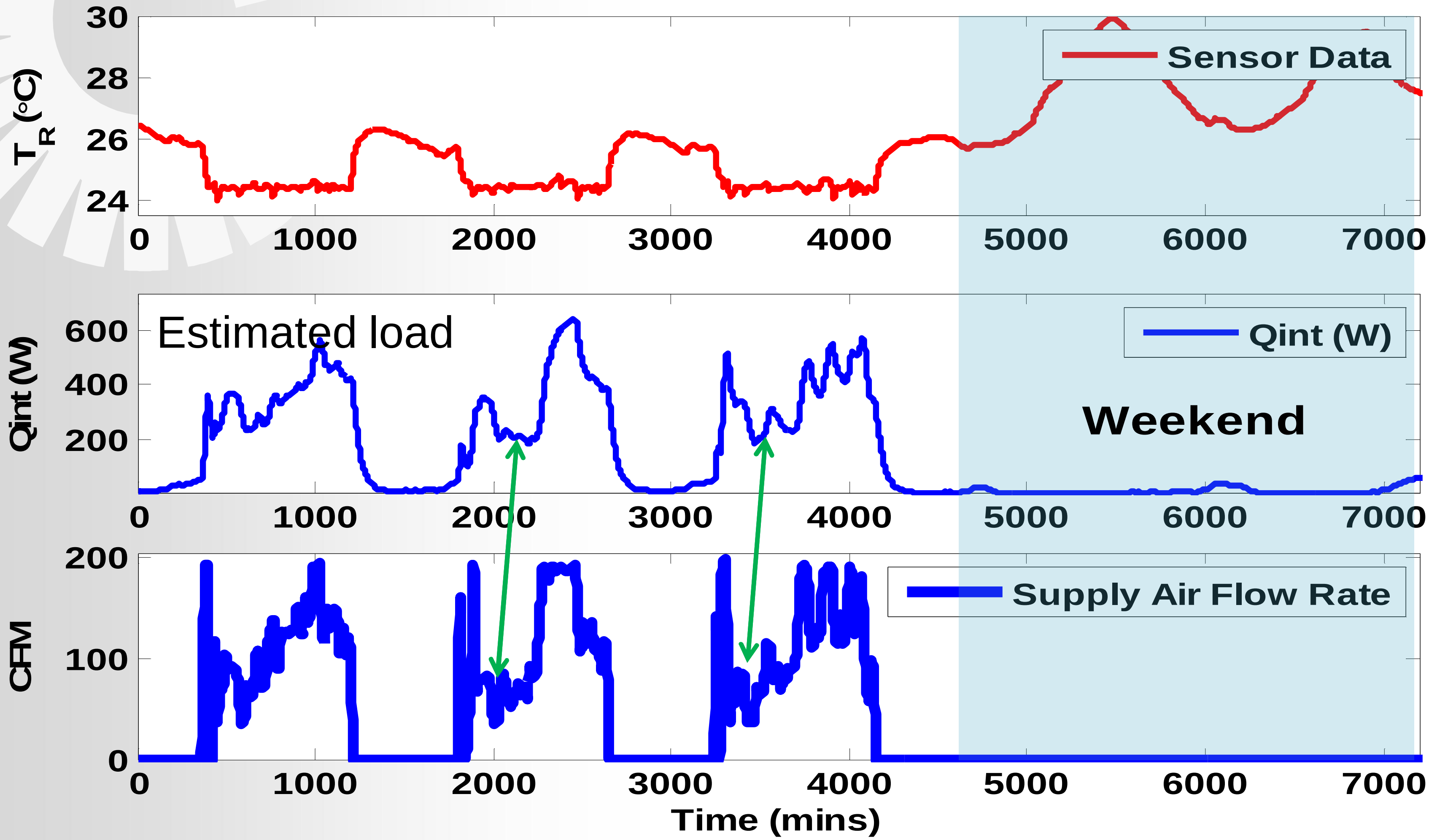
EKF Estimation Results External Zone DDV242

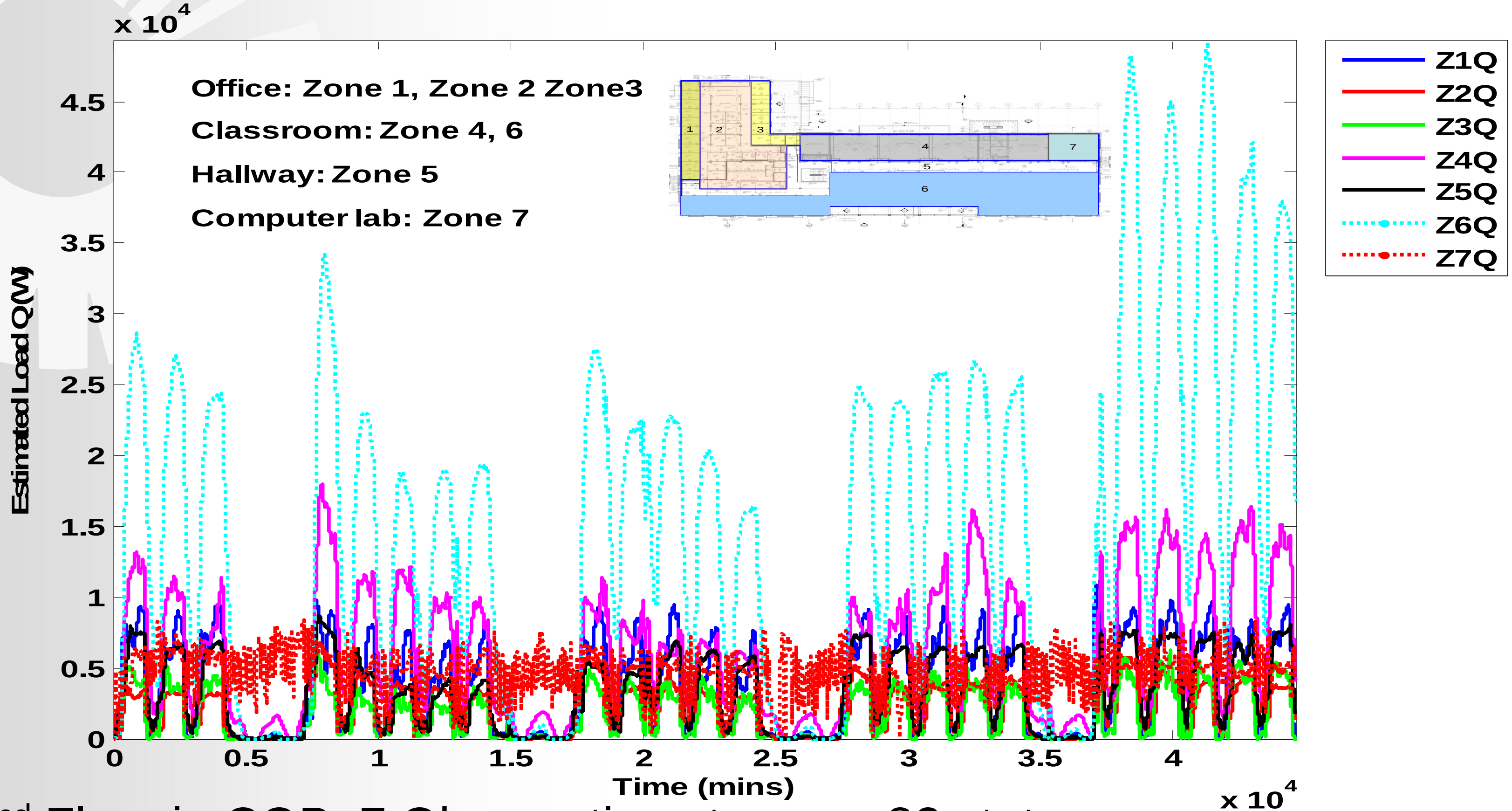




2 mins Interpolation DDV 242 – Aug 1st to Aug 5th 2007

- Solar calculation from whole building simulation program EnergyPlus

Multiple Scale Estimation Results for August 2007



- 2nd Floor in COB; 7 Observation streams; 82 states
- With soft constraints – Q > 0
- Solar calculation from EnergyPlus (using TMY2 data)
- Thermal resistances for windows (including frame) from E+, configuration and materials consistent with as built drawings

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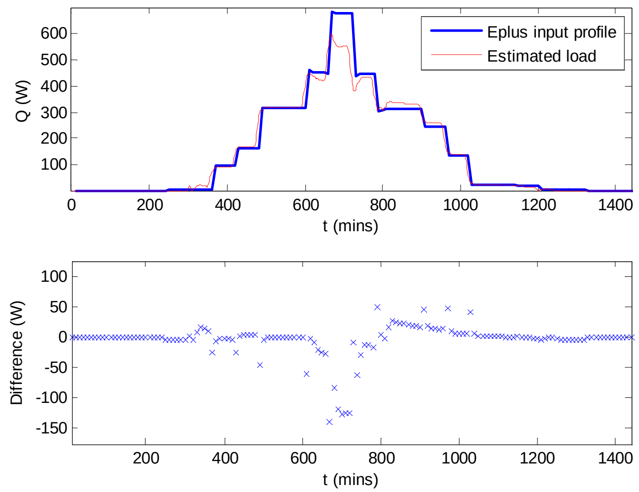
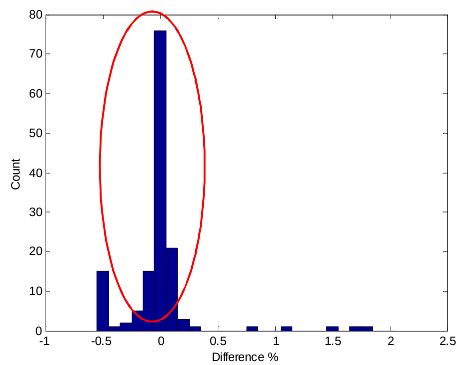
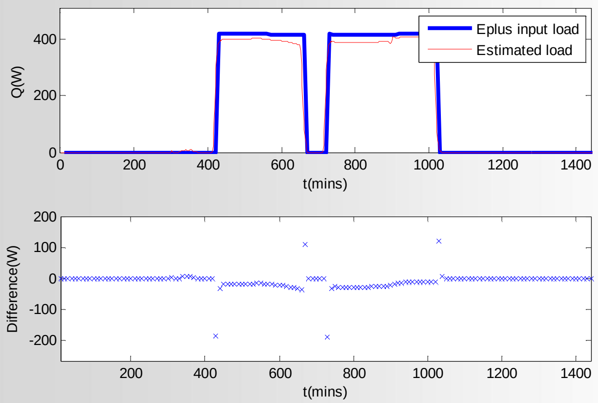
Simulation-Based Zonal Load Estimator Validation

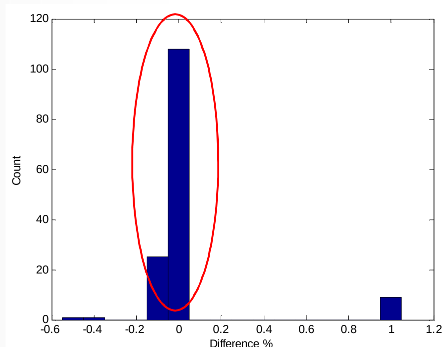




±10% error band: 73%

±20% error band: 82%





±10% error band: 93%

- Use COB Energyplus model* to generate data
- Procedure:
  - Assume load profile
  - Run E+ simulation
  - Outputs (zonal temps and air flow rates)from E+ → inputs to estimator
  - Run estimator
  - Compare estimated load with E+ input load profile
- Difference due to:
  - Radiation heat exchange

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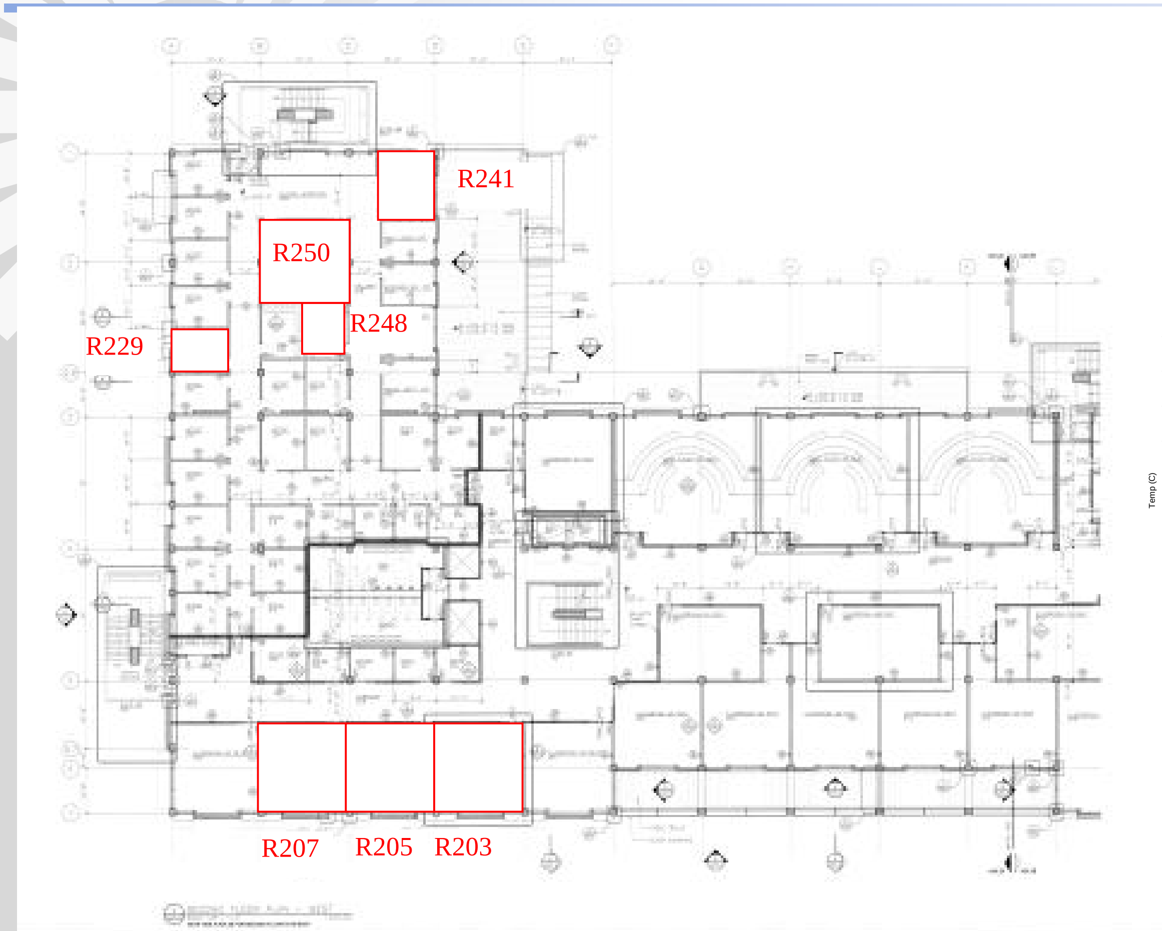
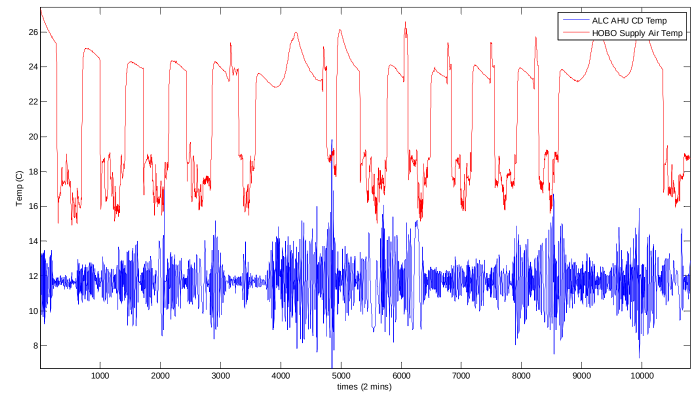
* Developed by D. Black (LBL)

Building Measurements



Second Floor of the Classroom and Office Building

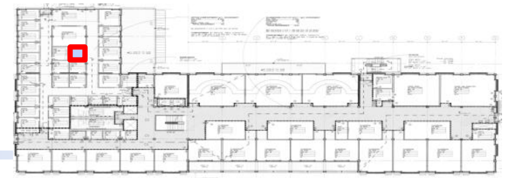
- Temp
- Humidity
- Lighting intensity

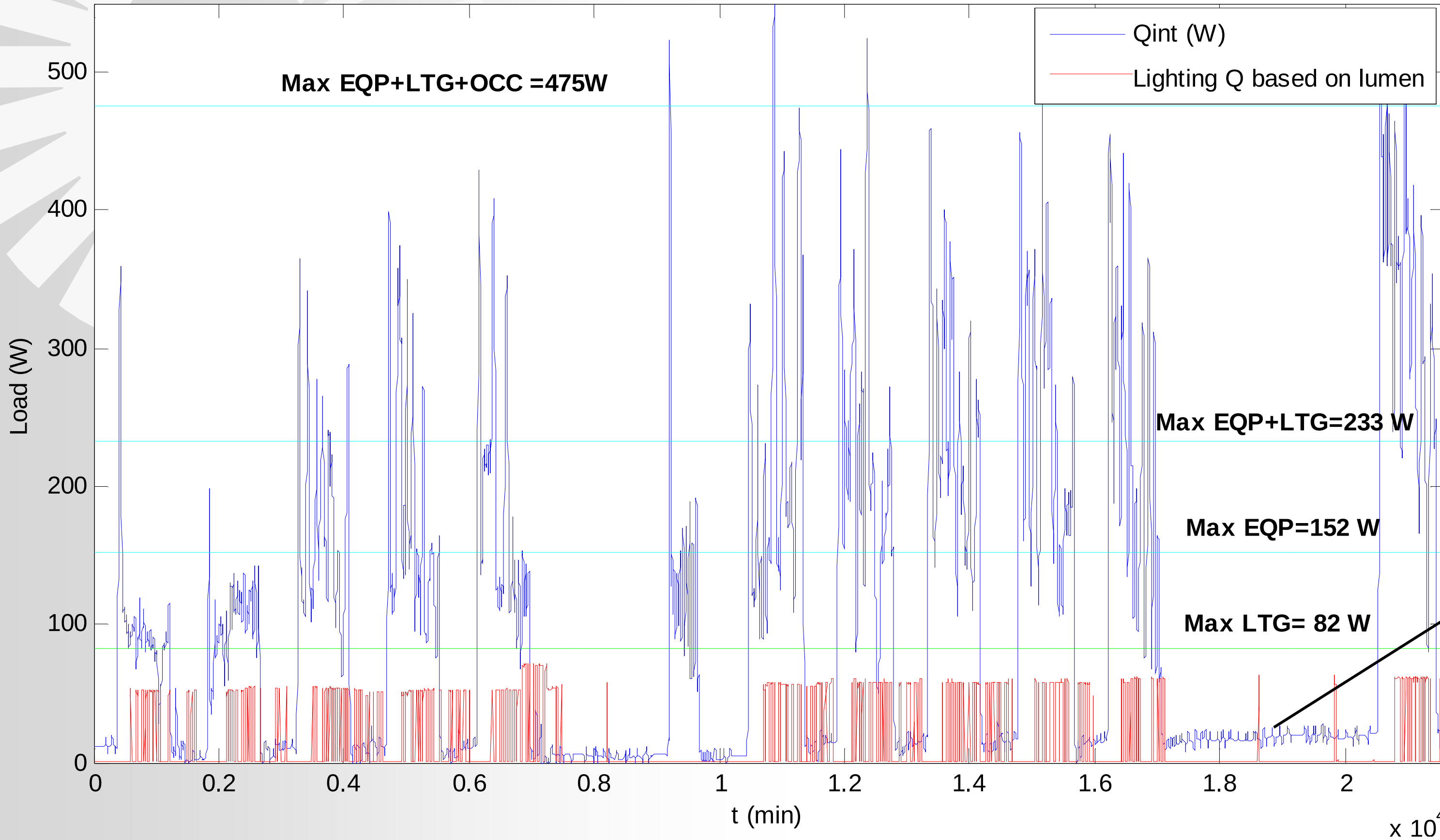


Zone supply air temp (red line)
=AHU CD temp (blue line) +5°C

- 14 portable sensors deployed in 7 rooms
  - Room temperature, supply air temperature
  - Lighting intensity

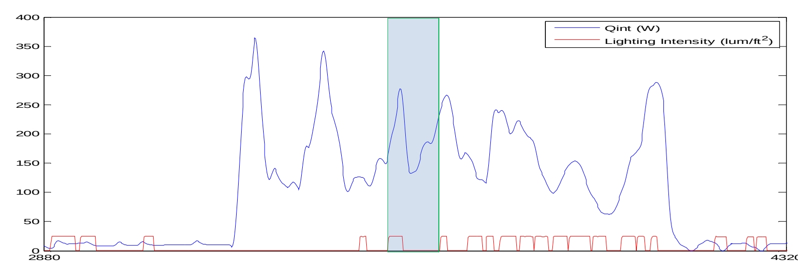
Estimator Calibration and Assessment with Portable Sensor Data





Non-zero loads due to
o Some equipment loads
o Estimator error
o Interzone air mixing

- 2 weeks in June 2009, interior room 248 (2 microwaves, 2 mini-fridges)
- Maximum values based on E+ inputs
- Zone supply air temp from portable sensor
- W= lm/ft^2*440ft^2*85lm/W /0.75



Estimated loads variation vs. measured lumen variation

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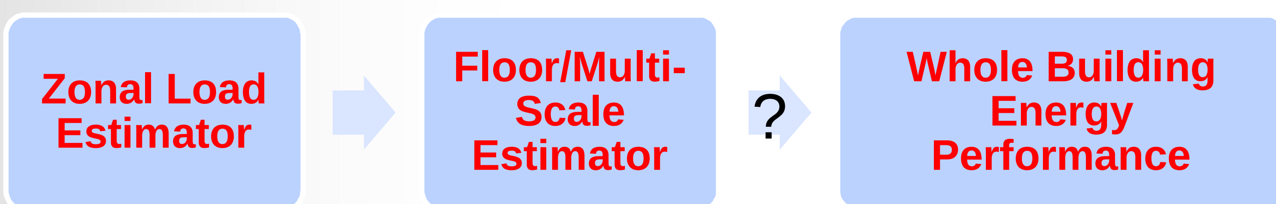
Conclusions

- Load estimator developed with reduced order building model and real time data.
  - Reusable and scalable to other buildings
- Accuracy of load estimator depends on:
  - Input parameters
    - Envelope thermal properties: resistance, capacitance…
  - Time series inputs : supply air flow rate and temperature
- Open question: Techniques to automatically correlate zonal load profiles/estimation to whole building performance & operational problems



Thank You

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Questions?