BUILDING AUTOMATION SYSTEM EMBEDDED HVAC SYSTEM PERFORMANCE DEGRADATION DETECTOR

Presented by:

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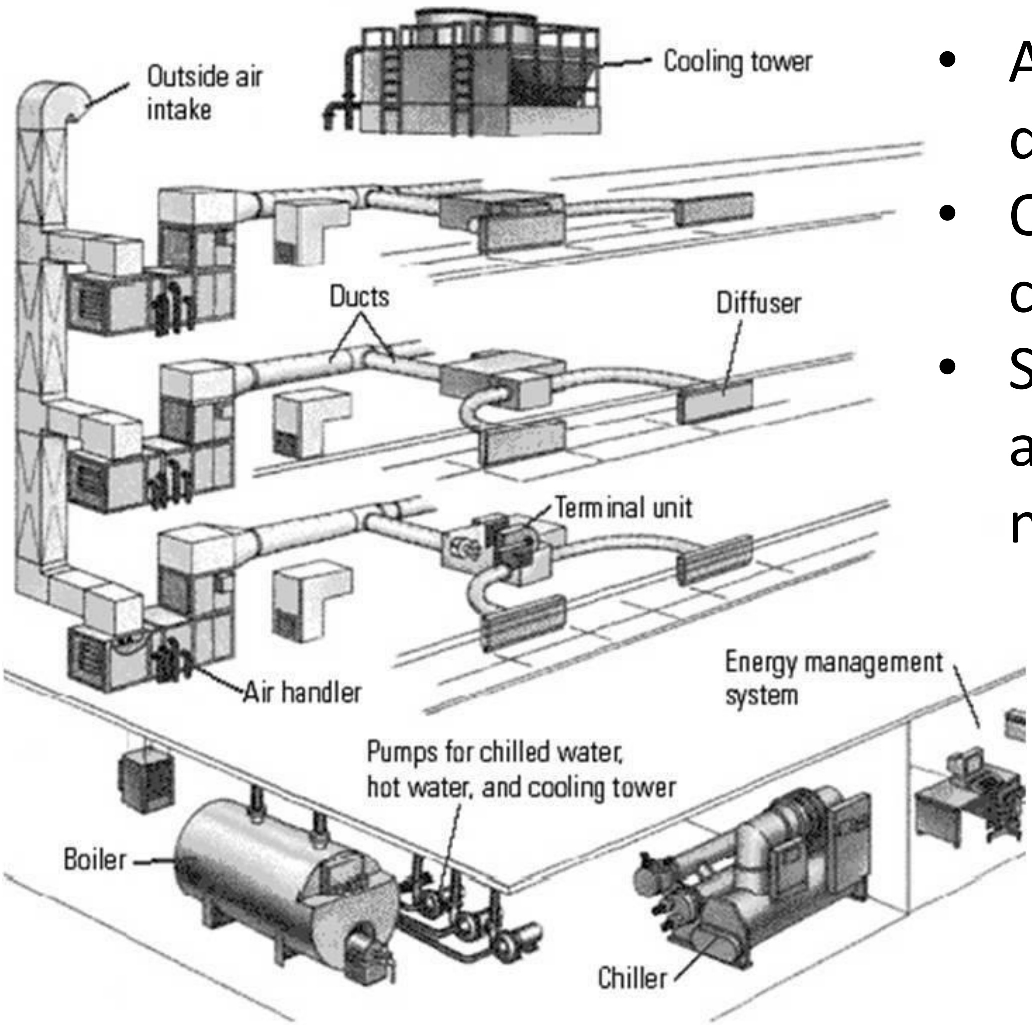
About Me

1993	1996	2000	2004	2009	Present
M.S. Degree (Harbin Institute of Technology)	Assistant Professor (BUCEA)	Ph.D. Degree (University of Nebraska)	VP of Engineering Technology at Bes-Tech Inc.	Assistant Professor (OU)	

- ✓ **Career transition** Bes-Tech Inc./**industry** to **academia**
- ✓ **Varied academic and professional experience** (**project manager**, professional engineer, **teaching instructor** and researcher)
- ✓ Focused on improving building energy efficiencies **(BEEL)**

Overview of a HVAC System



- A complicated system with dynamic load changes.
- Operational reliability is not critical as in other industries.
- Sensors installed are not adequate or accurate as needed.

Challenges of State-of-the-Art in FDD

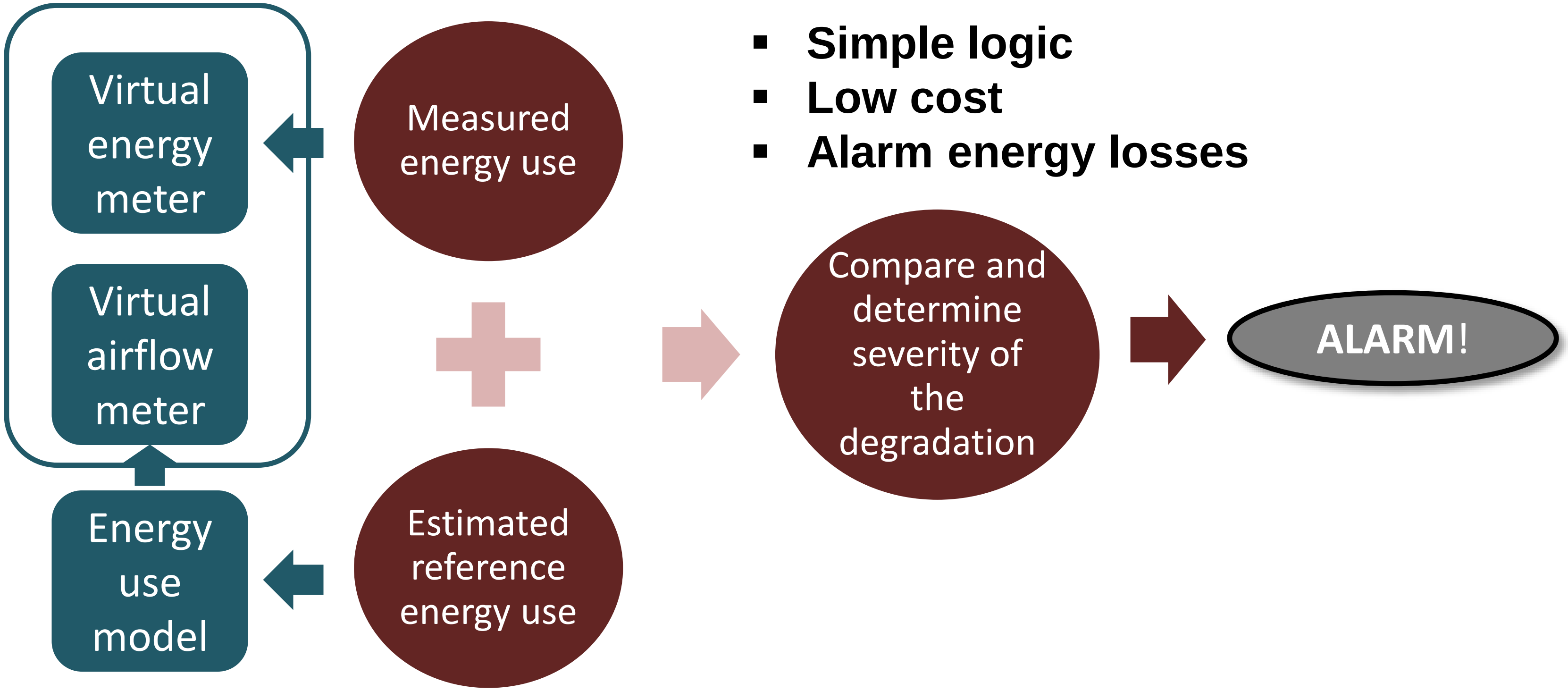
- Rule-based method: (House et al., 2001; Schein et al., 2003; Schein et al., 2006)
  - The rules are based on knowledge of how systems physically operate.
  - Faults are detected using qualitative (inequality) relationships.
  - Cons: The method does not provide indicators of the severity of faults.

- Model-based method: (Katipamula and Brambley, 2005a&b)
  - Use component models to predict the references of correct behavior of each component and compare it with measurements.
  - Cons:
    - Computational burden.
    - Require knowledge of the system and methods.

No commercial products available in the market.

BEEL Solution: Energy Monitor Based FDD

- **Simple logic**
- **Low cost**
- **Alarm energy losses**



What Is a Virtual Meter?

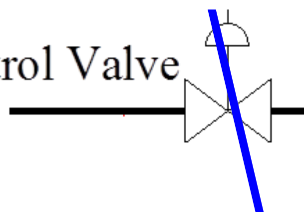
Low-cost accessory inputs

Difficult direct measurements

Characterize human CO_2 production rate by age, gender, etc.

Instant results

Virtual Sensor



$$Q_x = F_{L.x}(x)\sqrt{\Delta P_{L,x}}$$

Virtual Water and Air Flow Meters

Why?
- Flow meters are expensive
- Flow meters are usually intrusive
- Flow meters require long and straight duct/pipes to install

What?
Virtual measurements:

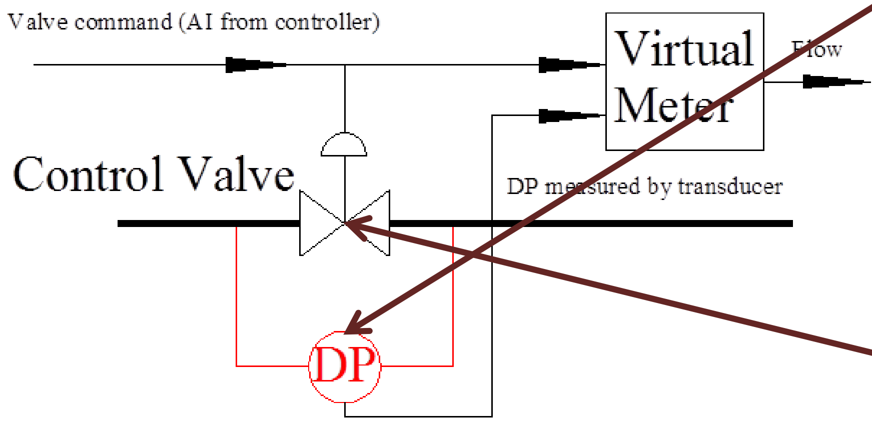
$$Y = f(a_1, a_2, a_3, \ldots a_m, X_1, X_2, X_3 \ldots X_n)$$

X_i: the sensed independent device operation variables

a_j: represent device characteristic, which can be determined empirically or analytically

Virtual Energy Meters in an AHU

<u>Virtual flow rate measurement:</u>



DP: Differential Pressure

$$Q_x = F_{L.x}(x)\sqrt{\Delta P_{L,x}}$$

$$F_{L.x}(x) = \sqrt{(C_v \cdot f(x))^2 N/[N + f^2(x)(1-N)]}$$

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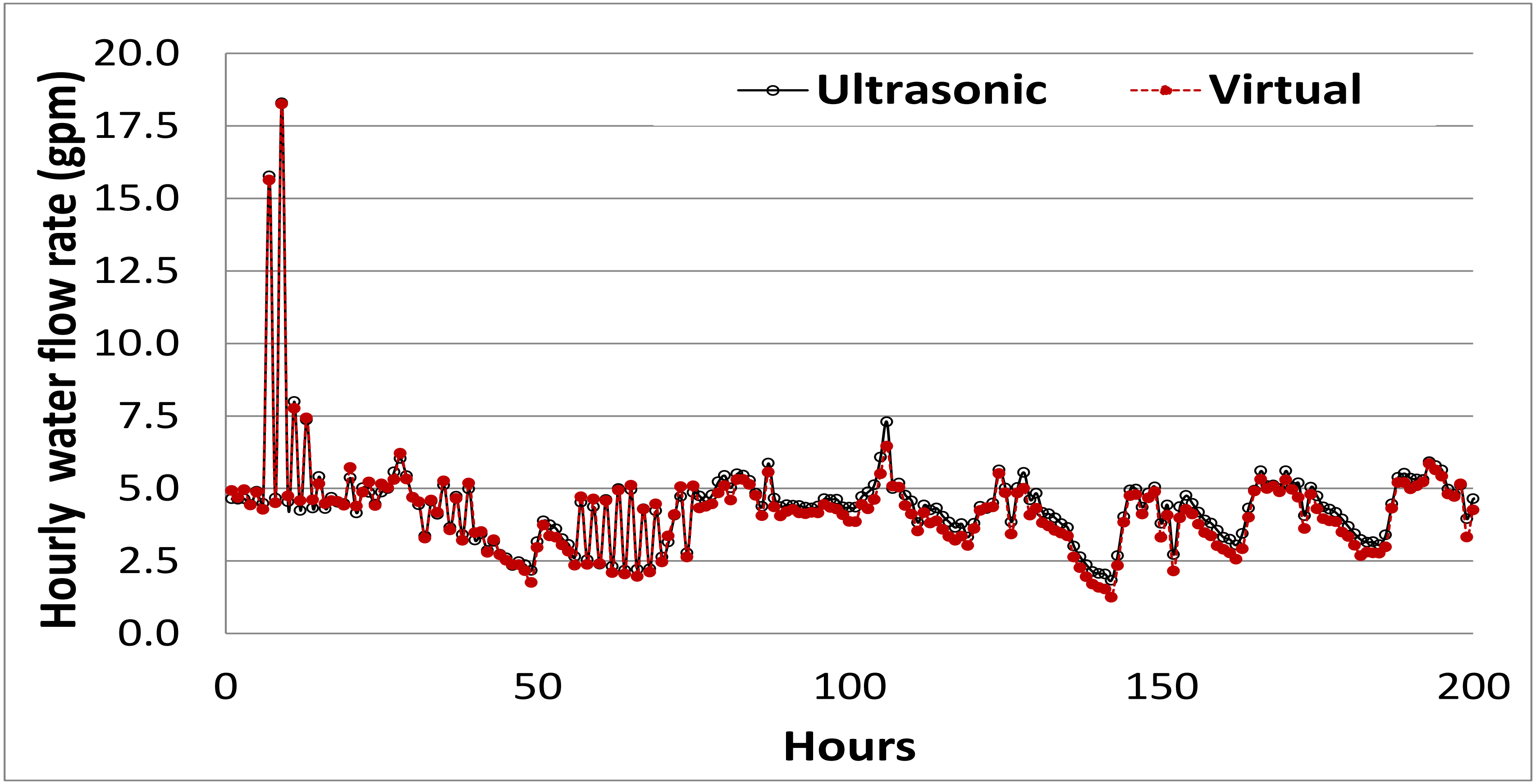
Virtual Energy Meters in an AHU



Results show 0.46% uncertainty at 95% confidence .

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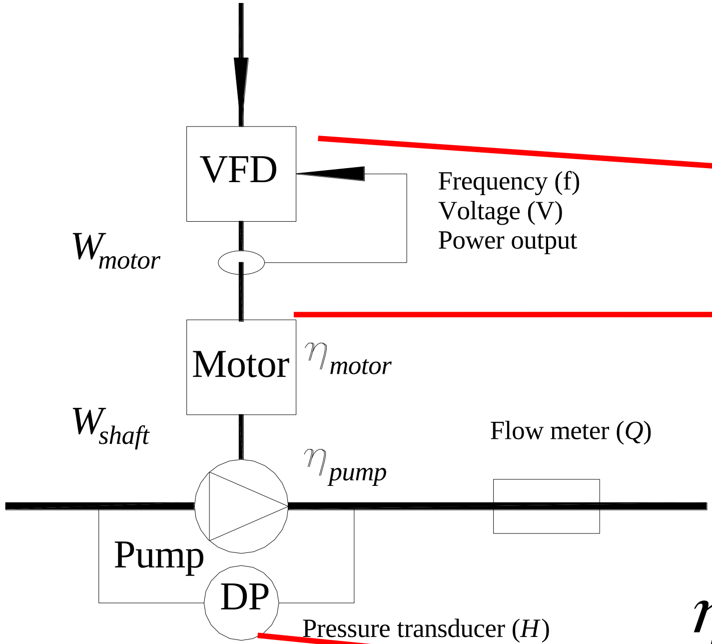
Virtual Fan/Pump Flow meters



$$\frac{\eta_{motor} \cdot \eta_{pump} \cdot W_{motor}}{H} = Q$$

- Direct measurement: H and Q
- Driven efficiencies

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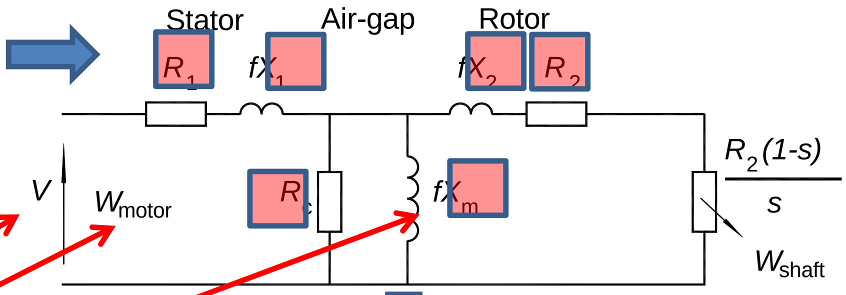
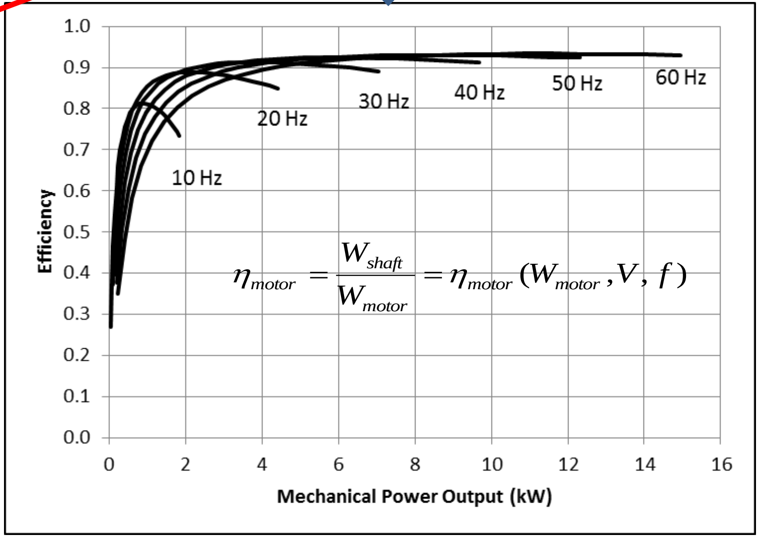
Motor Efficiency Model Using an Equivalent Circuit

Motor type	NEMA Design B							
Size (HP)	20							
Speed (RPM)	1800							
Full load speed	1766							
Voltage (V)	460							
Load (%)	25%	51%	75%	88%	100%	115%	124%	148%
Efficiency (%)	43%	66%	76%	79%	80%	81%	82%	82%
Power factor (%)	89%	93%	93%	93%	93%	93%	92%	91%





Motor efficiency can be expressed as a function of power voltage (V) and frequency (f) as well as motor input power (W_{motor}) for a given motor if these six circuit parameters are known.

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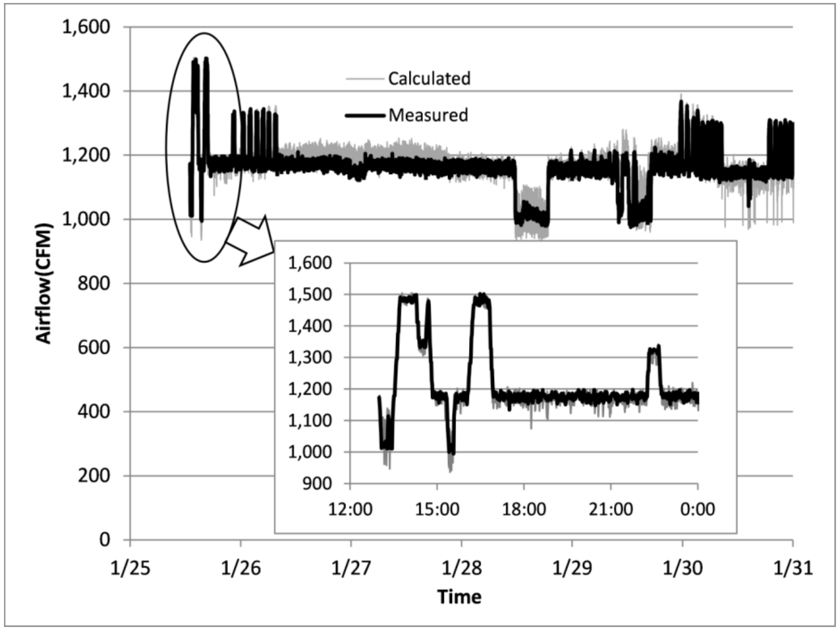
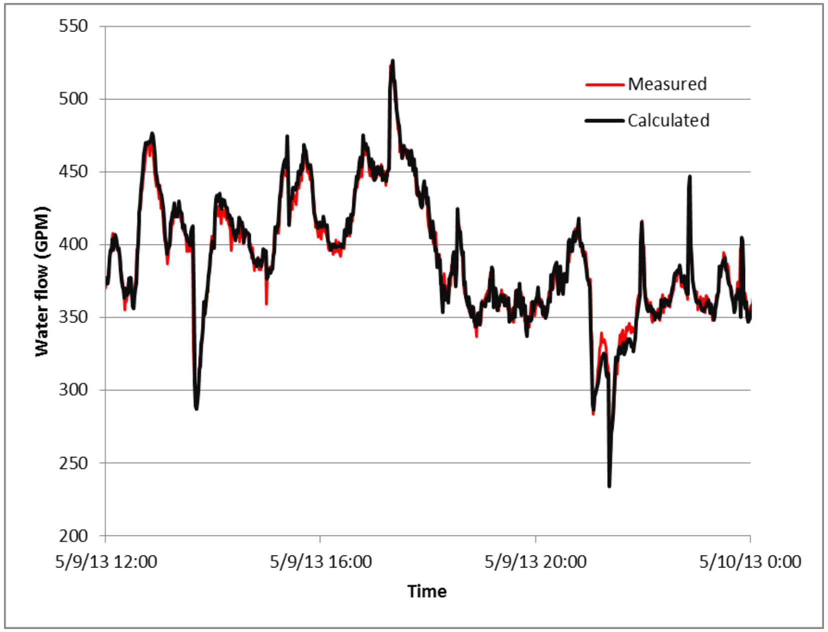
Virtual Fan/Pump Flow Meters



Virtual airflow measurements



Virtual water flow measurements

R^2 is 0.81 for the airflow meter and 0.973 for the water flow meter.

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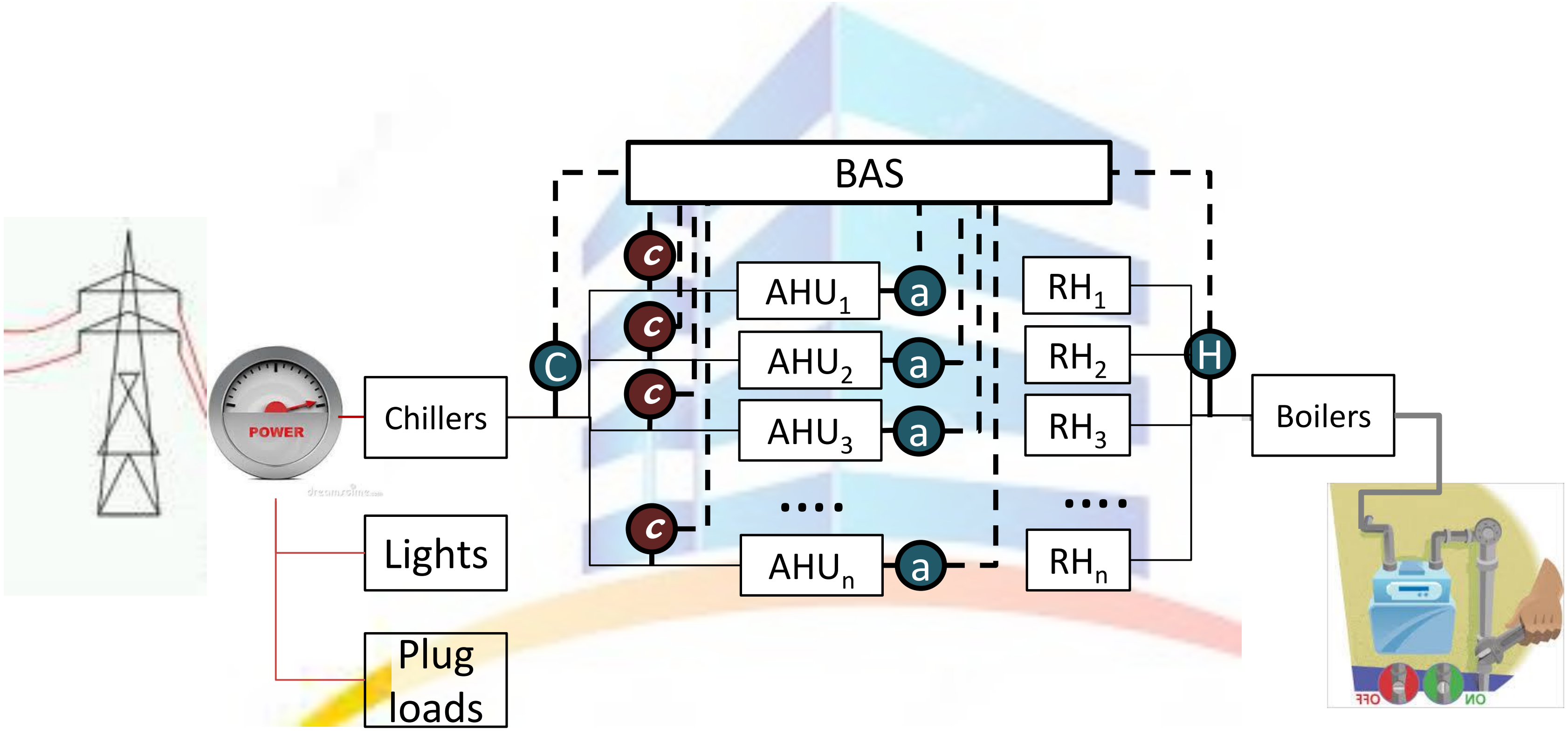
Impact of Virtual Meters:
High-Resolution Metering Capacity in Buildings



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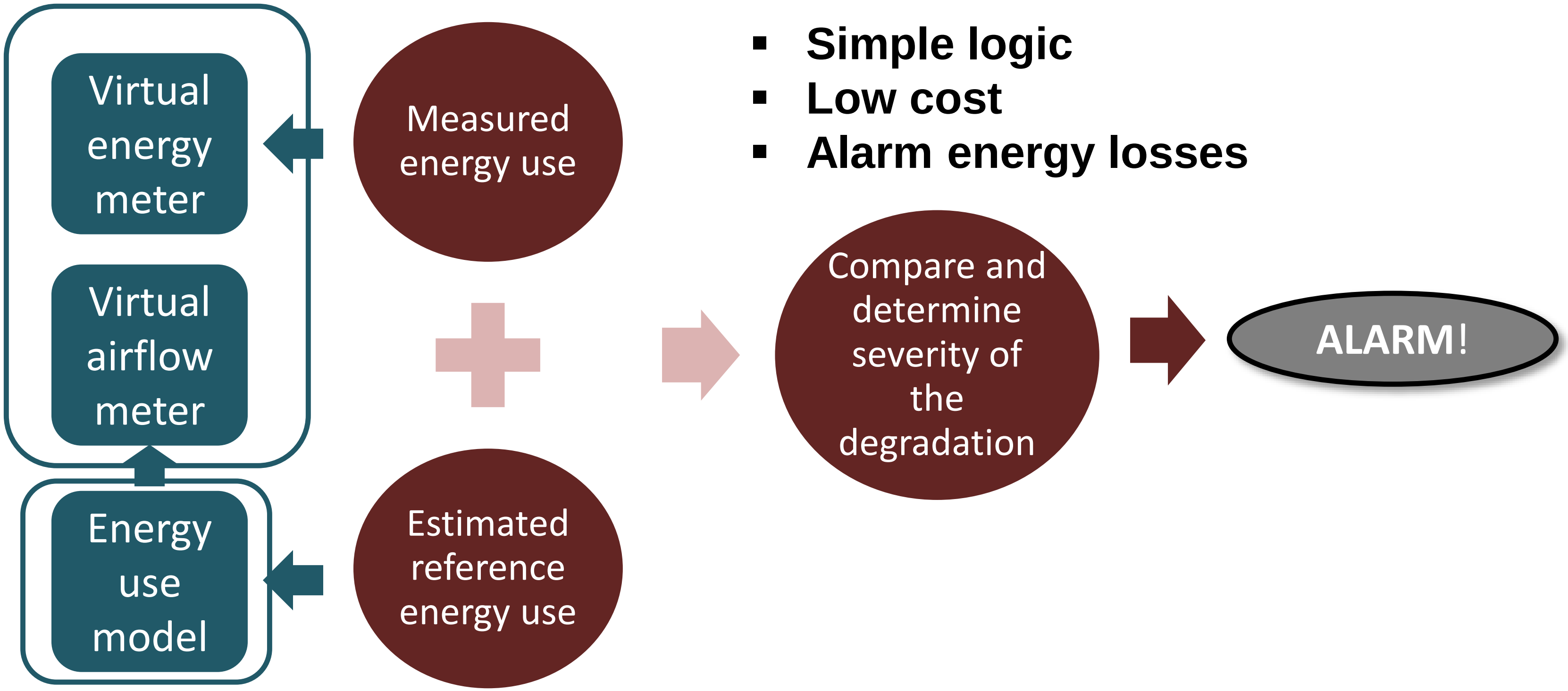
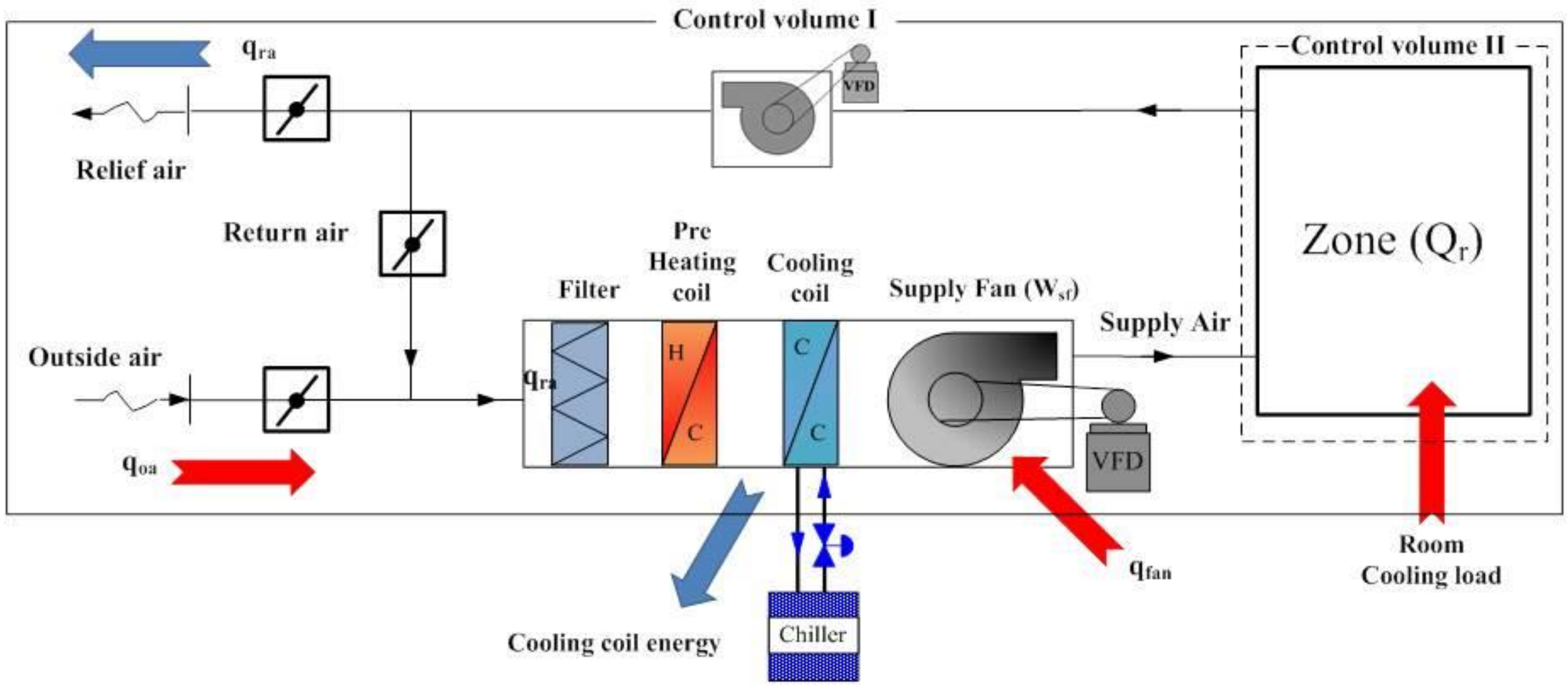
BEEL Solution: Energy Monitor Based FDD



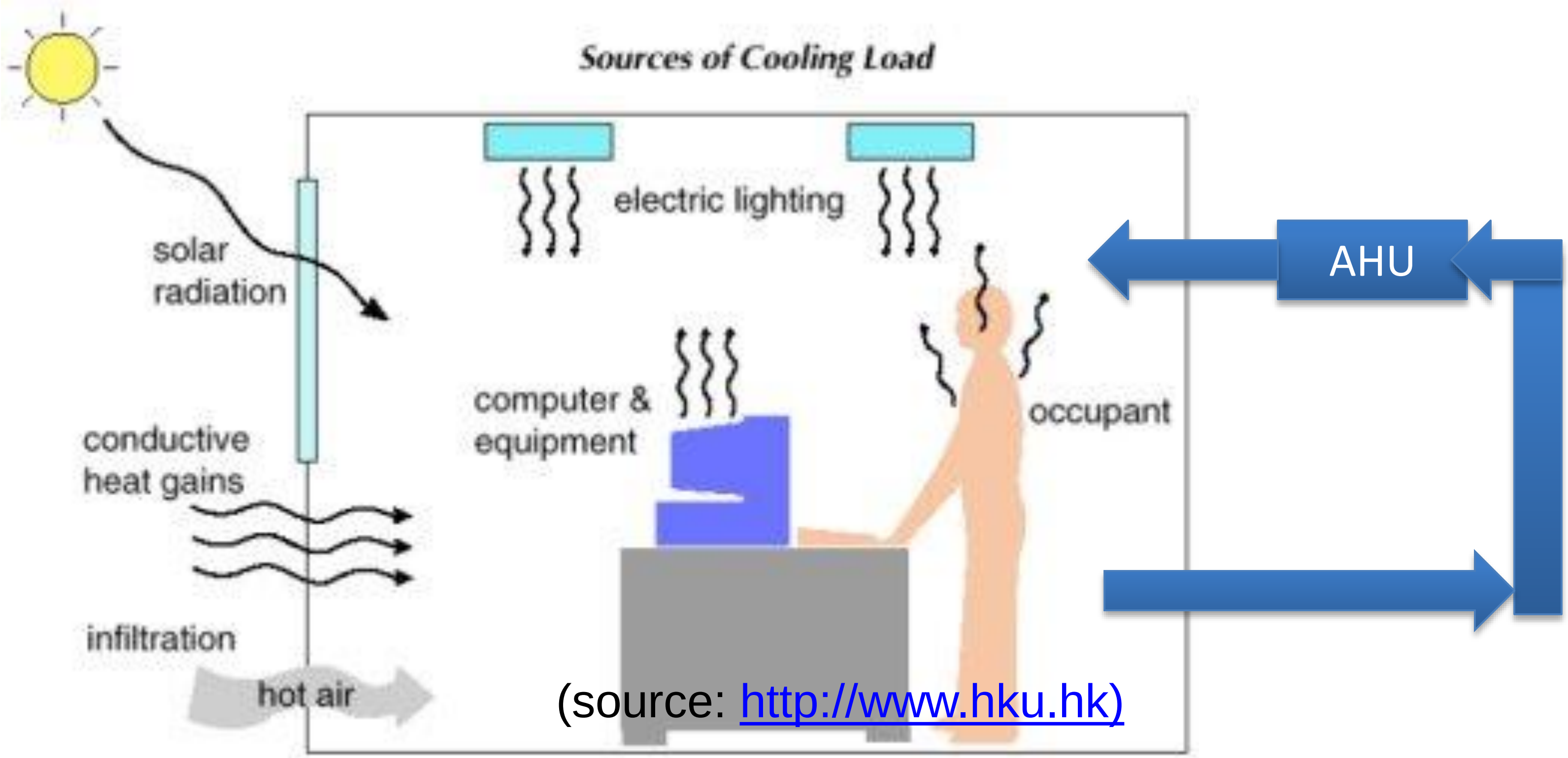
- Simple logic
- Low cost
- Alarm energy losses

Reference Energy Use



Cooling coil load = Fan heat load + Outdoor air load + Zone load

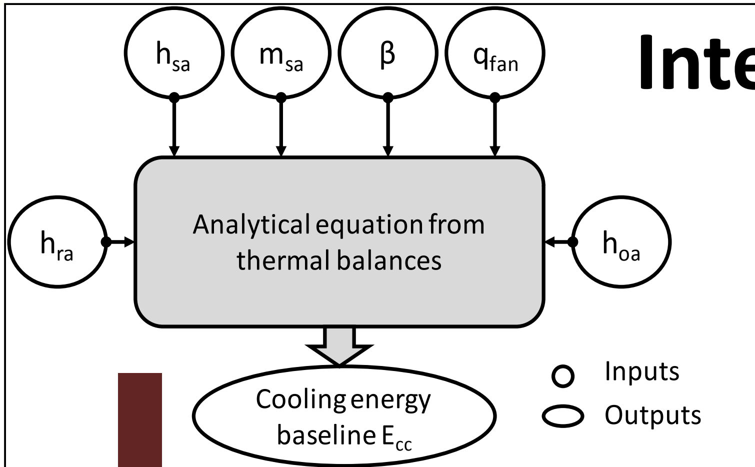
Zone Load



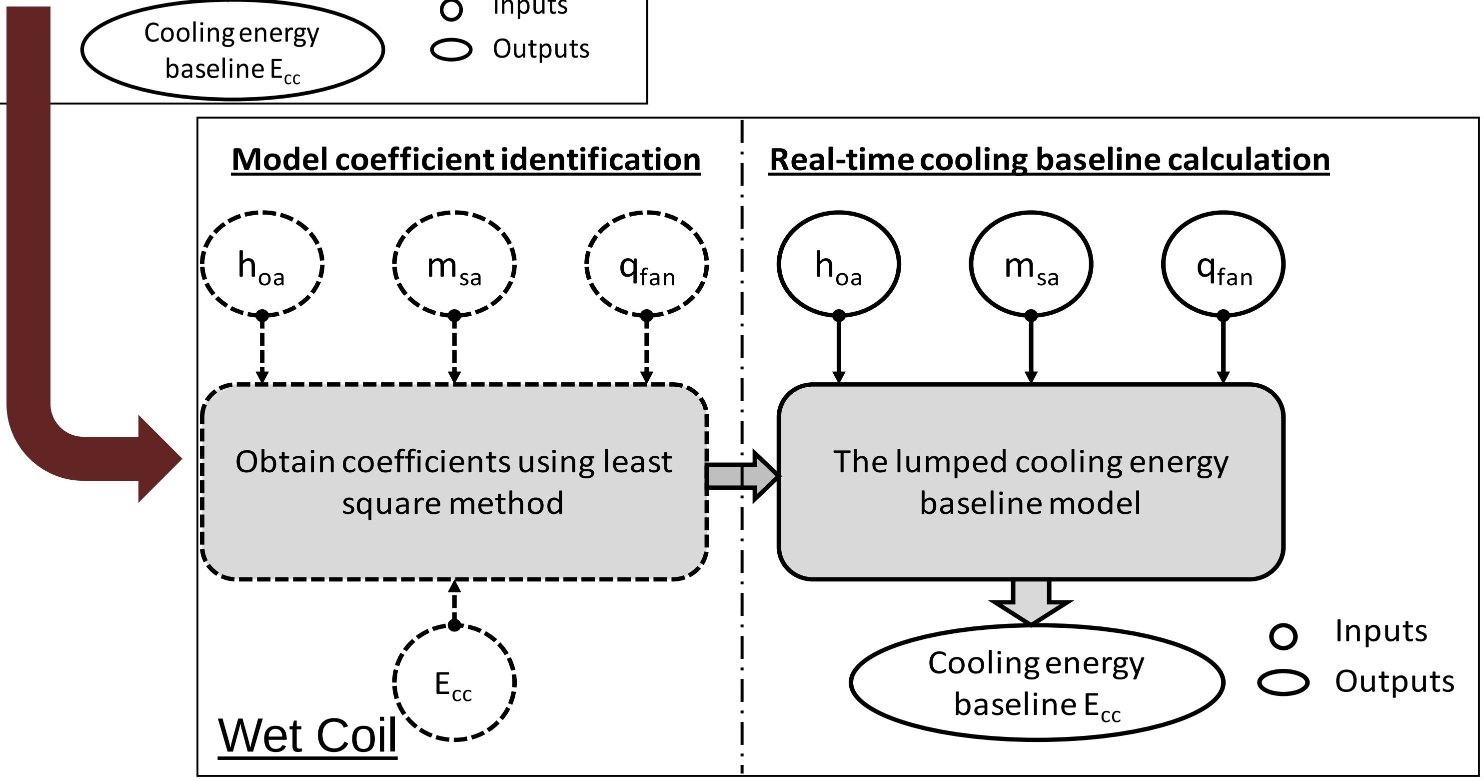
(source: http://www.hku.hk)

- Use AHU output (Integrated energy use model)

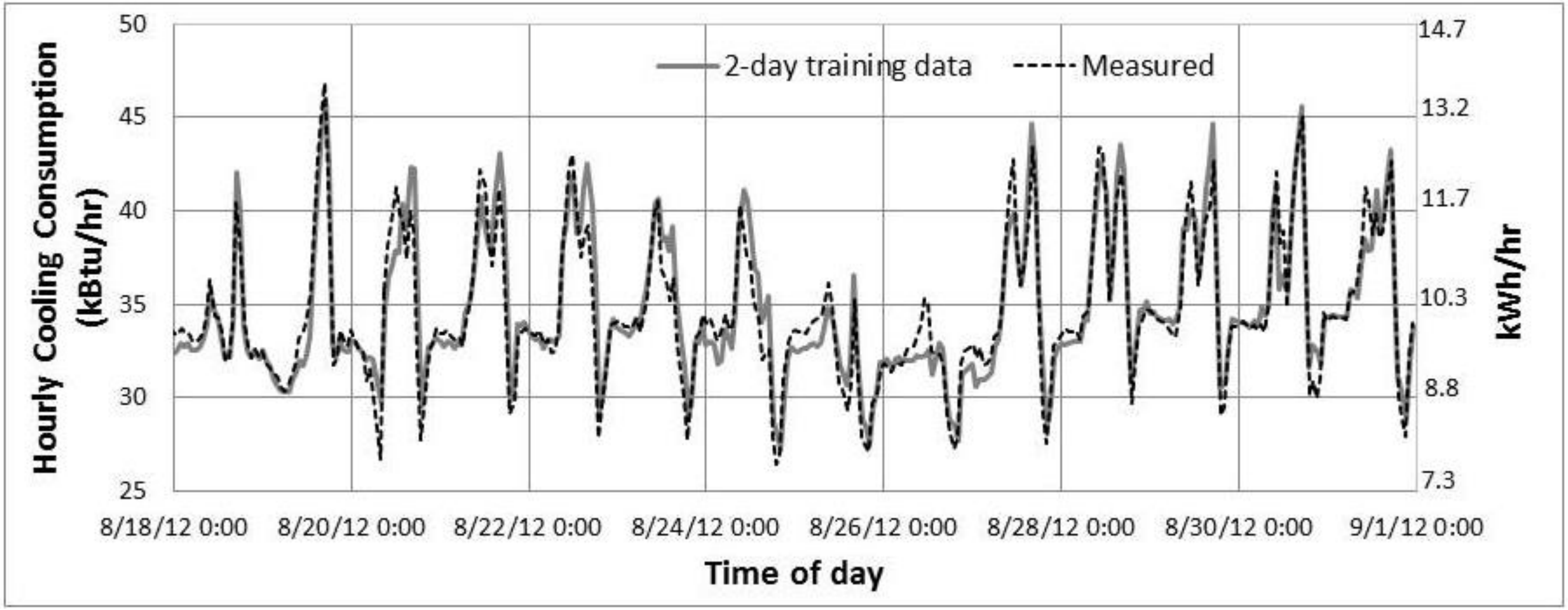
Integrated Energy Use Models



$$Cooling\ coil\ load = Fan\ heat\ load + Outdoor\ air\ load + Zone\ load$$

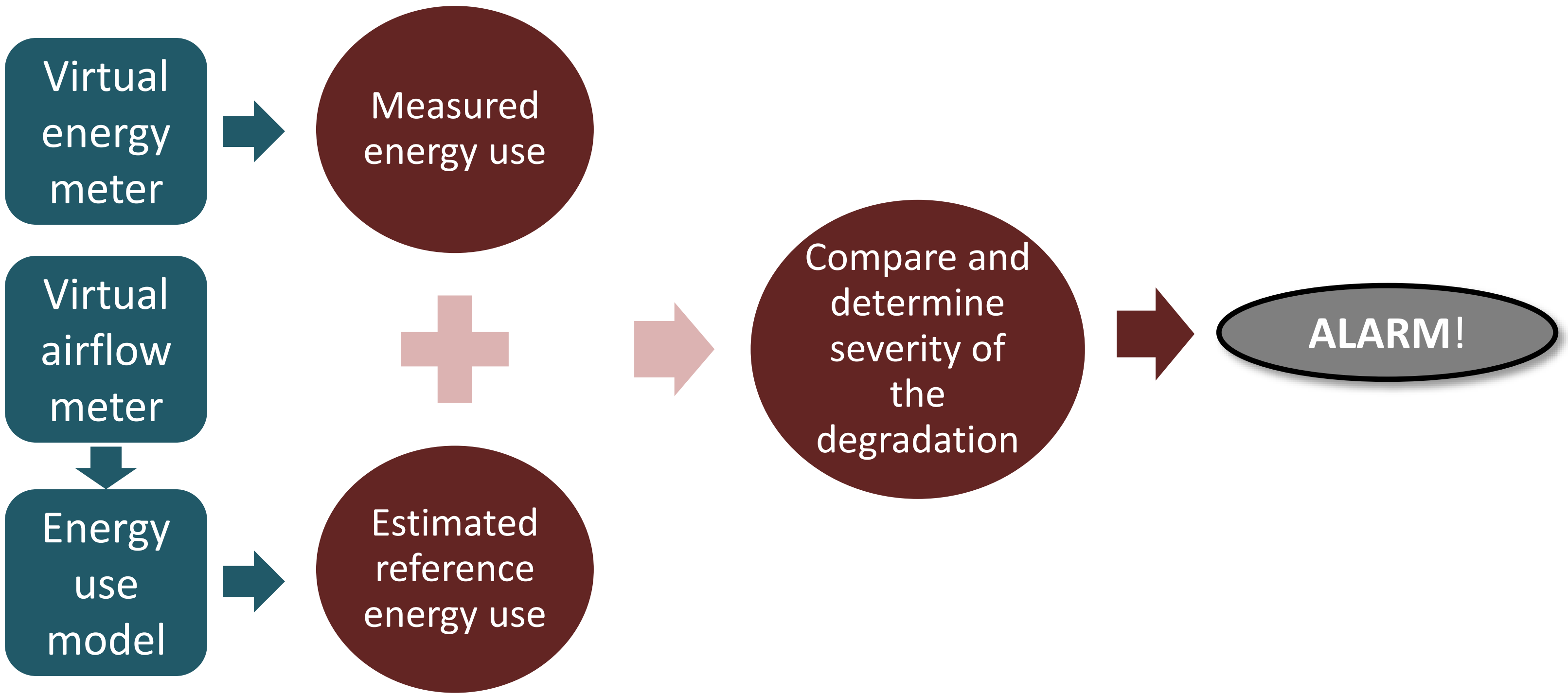


Comparison of Measured and Calculated Cooling Energy Use



Results show approximately ±2.5kBtu/hr error with 95% confidence for an AHU of the size of 96kBtu/hr.

Technology Summary



- Real-time energy use monitor of sub-systems
- Real-time diagnosis through energy use comparisons
- Fault severity identification

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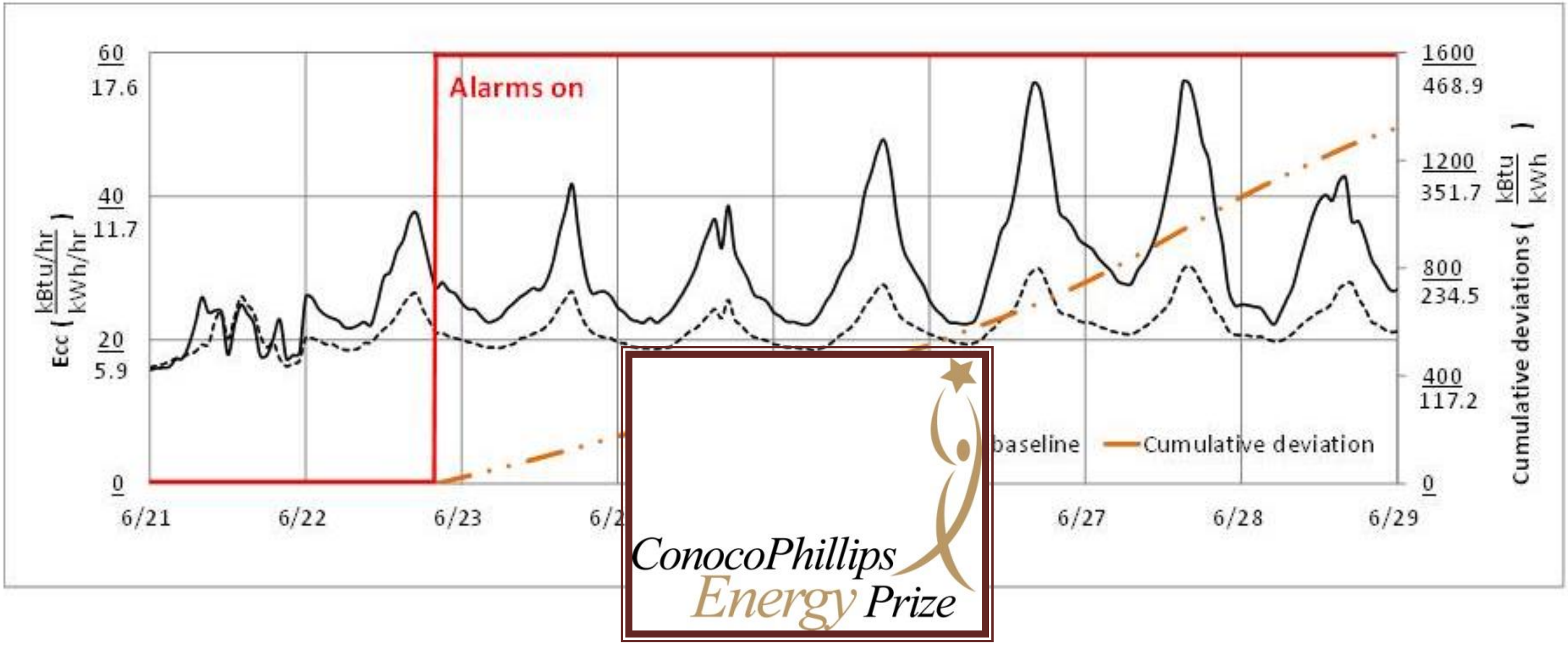
Experimental Validation



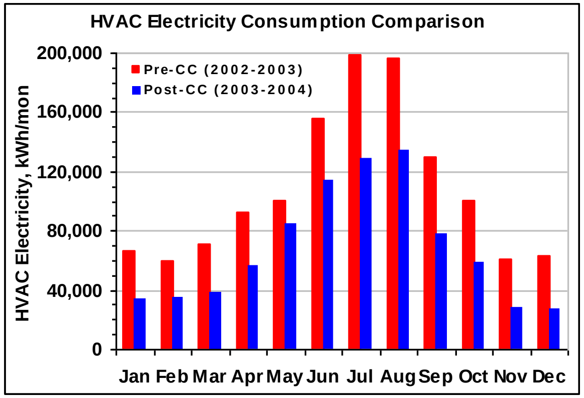
BEEL along with partners was awarded $947k by DoD ESTCP office to evaluate the potential for application of the technology across the DoD buildings portfolio.

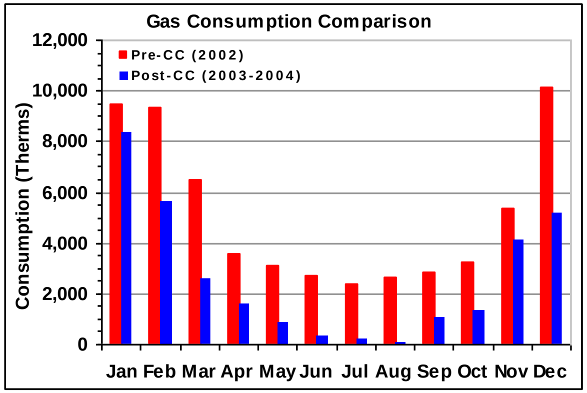
ESL-IC-14-09-13

15% to 30% Energy Saving Potentials in Buildings

Building 1

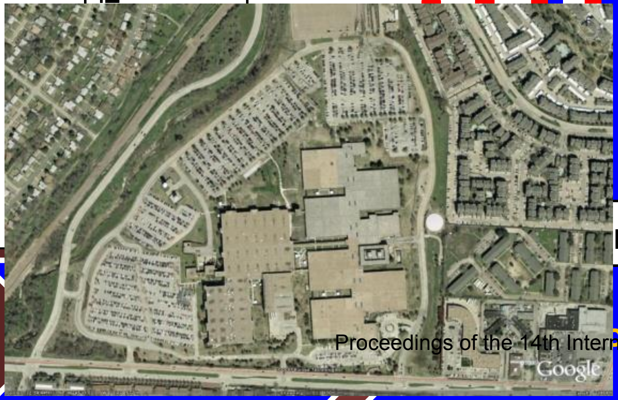
❑4-story office building built in 2001	❑195,580 square feet
❑Two Single Duct VAV AHUs	❑Two centrifugal chillers
❑Ten boilers	❑Advanced BAS system

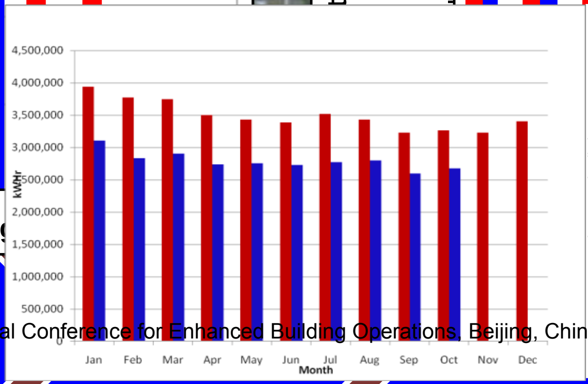


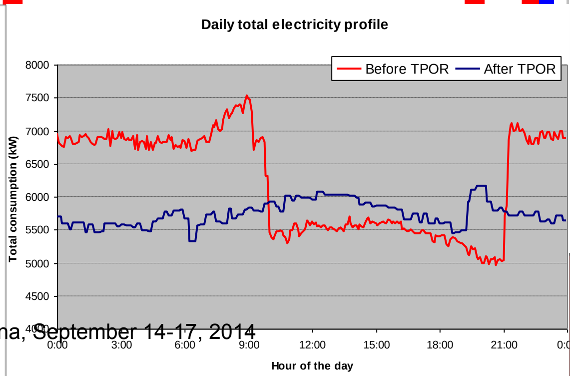


Building 2

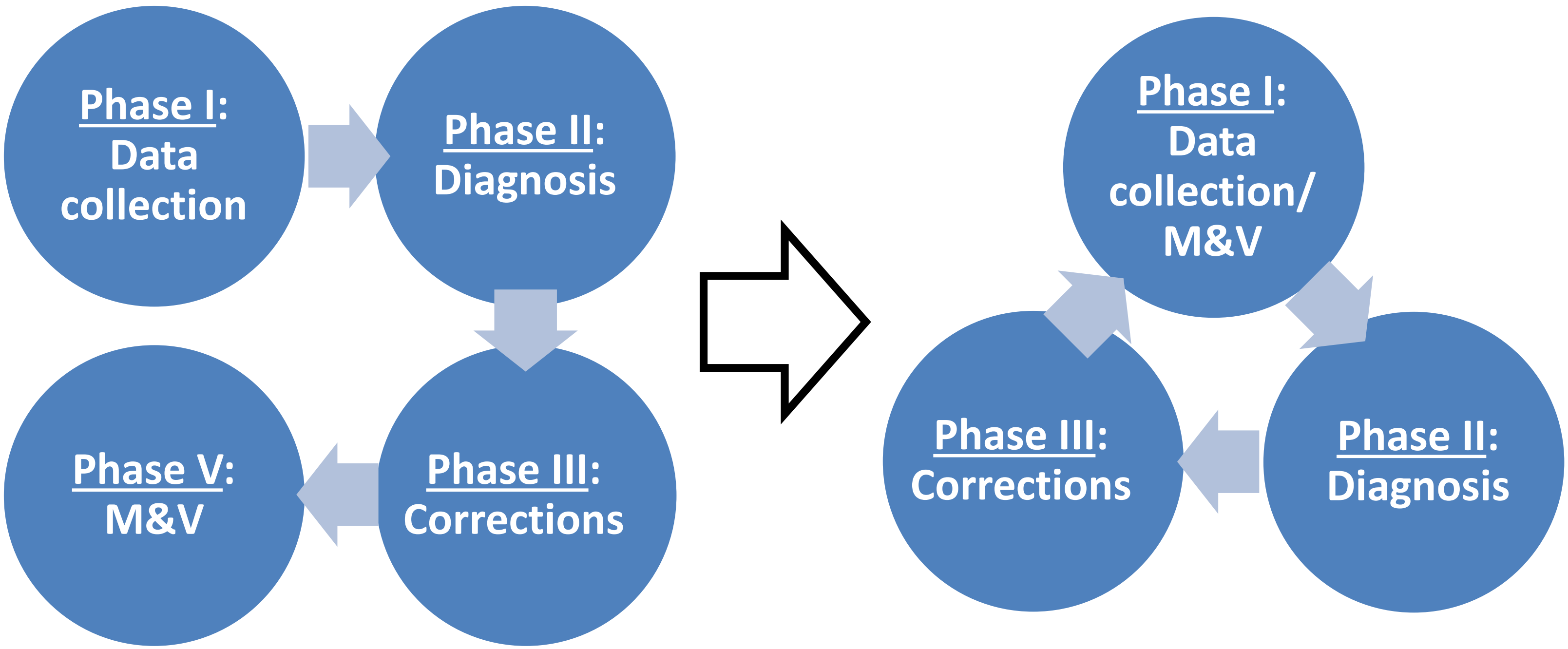
❑1-story office and lab building with 1,200,000 sq.ft.	❑97 Single Duct VAV AHU and 35 Single Zone AHU
❑2,255 VAV terminal boxes and 57 fan powered boxes	▪4 chillers: 2 chillers @1200 ton, 2 chillers @900 ton
▪2.7 million gallon thermal storage tank (chilled water)	❑TAC/CSI iNet 7 DDC control







Impact of BEEL Technology



Current Industry Practice

BEEL Approach

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Acknowledgements

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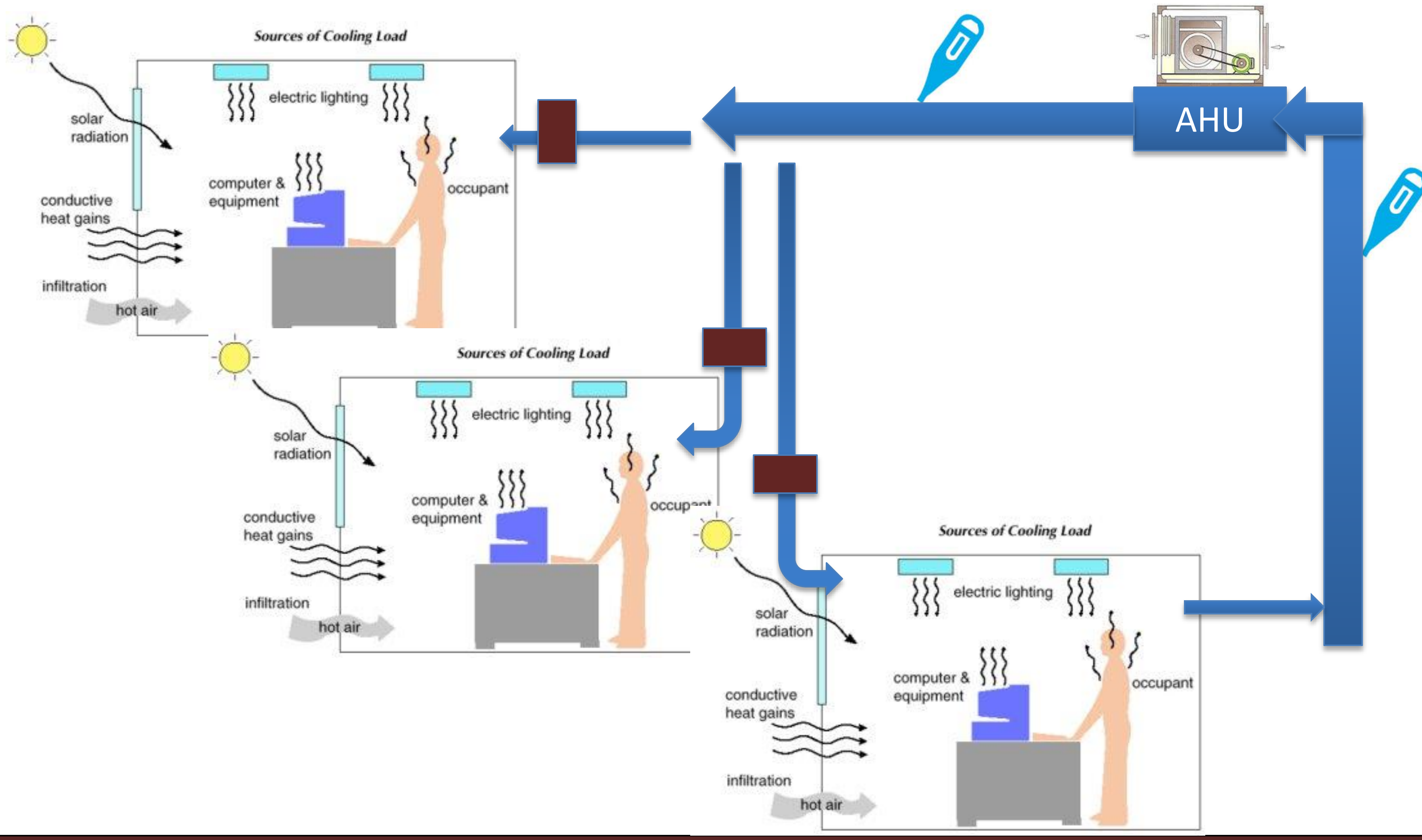
University of Miami

Dr. Mike Brambley
PNNL

Funding agencies:

1. PNNL (2011): Summer research.
2. ASHRAE (2011-2013): Developing standard procedures for filling climate data gaps for use in building performance monitoring and analysis.
3. DOE Building Technologies Office (2012): Develop and test virtual air-handler energy use performance monitor.
4. ASHRAE (2014-2016): Survey of particle production rates from process activities in pharmaceutical and biological cleanrooms.
5. DoD ESTCP office (2014-2017): Demonstration of a building automation system embedded performance degradation detector using virtual water/air flow meters.

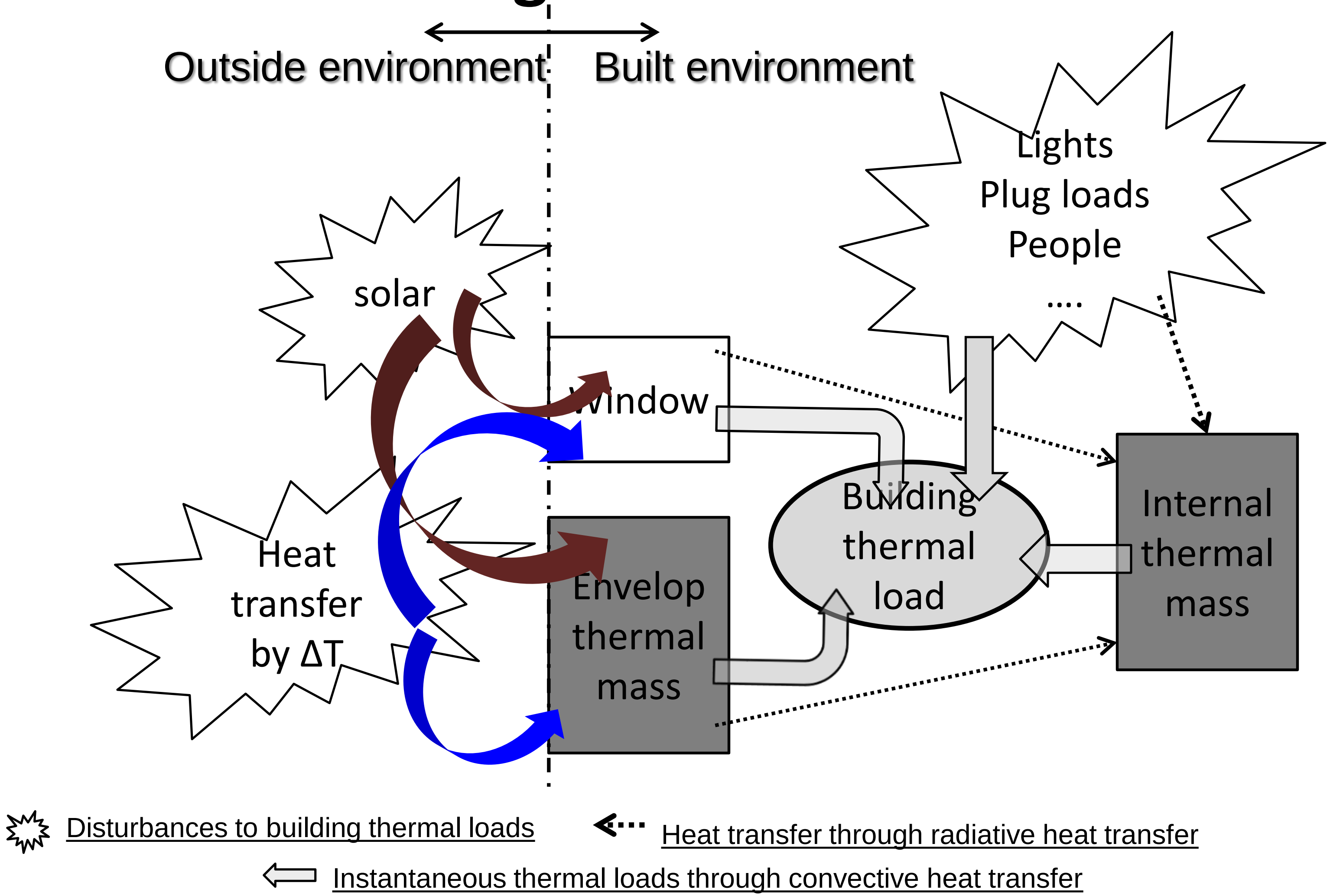
Zone Load


Sources of Cooling Load
electric lighting
solar radiation
computer & equipment
occupant
conductive heat gains
infiltration
hot air
AHU

Reference Energy Use

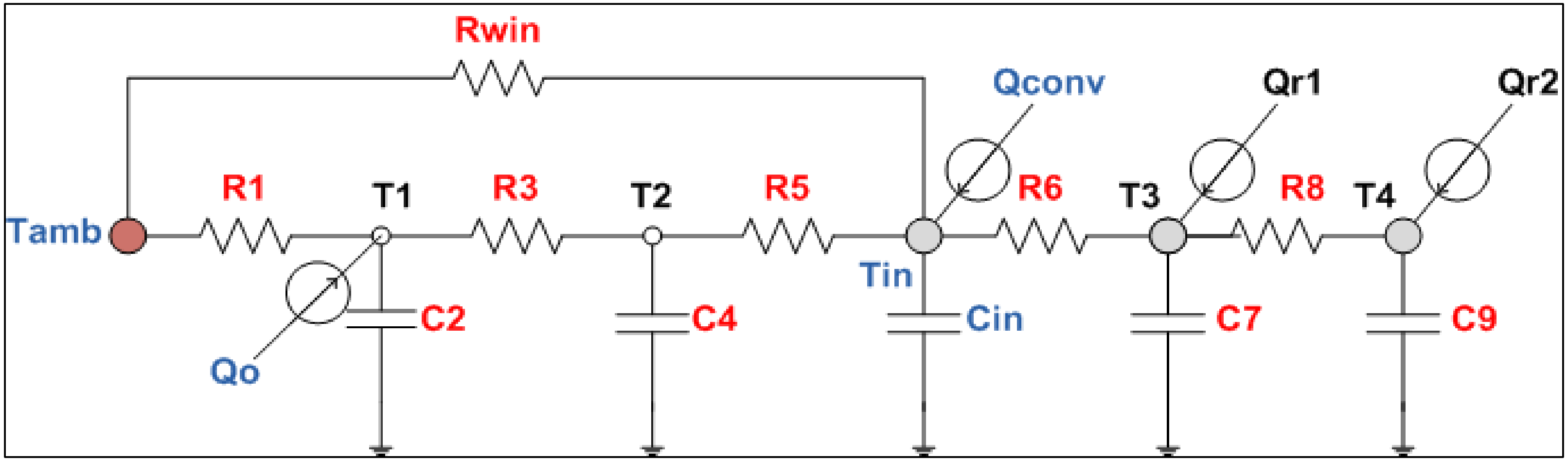
- Near term solution: integrated energy use model using AHU heat extraction rate
- Long term solution: Resistor-Capacitor (R-C) model to directly calculate zone load

Building Load Generation



R-C Model

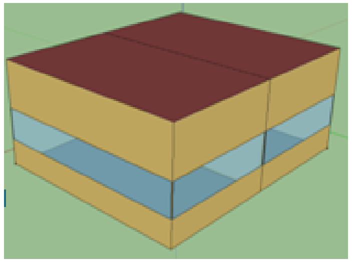
Aim is to develop and validate a computationally efficient load model for real-time load calculations.

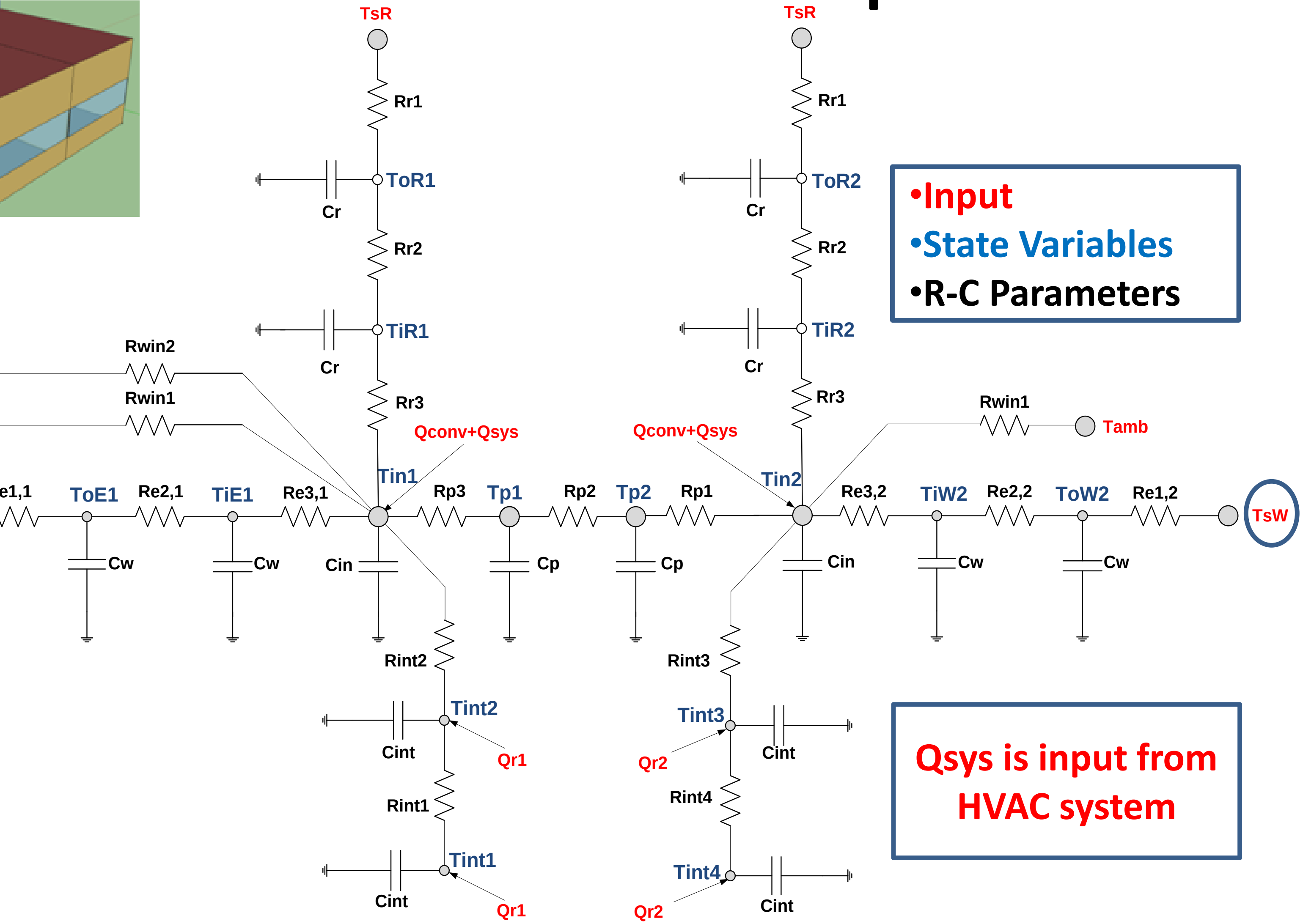


3R2C model for Building Envelope

2R2C model for Building Internal Mass

Thermal Model Development





- **Input**
- **State Variables**
- **R-C Parameters**

Qsys is input from HVAC system

R-C Model

$$\frac{dT_n}{dt} = -\frac{1}{C_n}\left(\sum_{i=1}^{j}\frac{1}{R_i}\right)T_n + \frac{1}{C}\left(\sum_{i=1}^{j}\frac{1}{R_i}T_i\right) + \frac{1}{C}\sum_{m=1}^{p}Q_m$$

where T_n= temperature of nth node;
j=total number of temperature branches connected to node n; T_i= temperature of ith branch, connected to node n;
p=total number of heat flux branches (such as convection, radiation, and system input) connected to node n;
Qm= heat flux of mth branch connected to node $n.$;
C_n= capacitance of node n;
R_i= resistance of branch between T_n and T_i

R-C Model Analytical Solutions

$$\dot{T} = AT + BU$$

$$A = \begin{pmatrix} a_{1,1} & \cdots & a_{1,24} \\ \vdots & \ddots & \vdots \\ a_{24,1} & \cdots & a_{24,24} \end{pmatrix}; \boldsymbol{T} = \left[T_{1,1}\ \ T_{2,1} \ldots\ T_{24,1}\right]' \ \ B = \begin{pmatrix} b_{1,1} & \cdots & b_{1,10} \\ \vdots & \ddots & \vdots \\ b_{24,1} & \cdots & b_{24,10} \end{pmatrix}; \ \boldsymbol{U} = \left[U_{1,1}\ \ U_{2,1} \ldots\ U_{10,1}\right]';$$

$$T_{t+\delta} = e^{A\delta} T_t + \int_t^{t+\delta} e^{A(t+\delta-\tau)} B\boldsymbol{U}(\tau) d\tau$$

$$T_{t+\delta} = e^{A\delta} T_t + \int_t^{t+\delta} e^{A(t+\delta-\tau)} B \left[\boldsymbol{U_t} + \frac{(\tau - t)}{\delta} (\boldsymbol{U_{t+\delta}} - \boldsymbol{U_t})\right] d\tau$$

Matrix decomposition method is use to obtain analytical solutions.

$$A = CDC^{-1} \qquad\qquad e^{At} = Ce^{Dt}C^{-1}$$

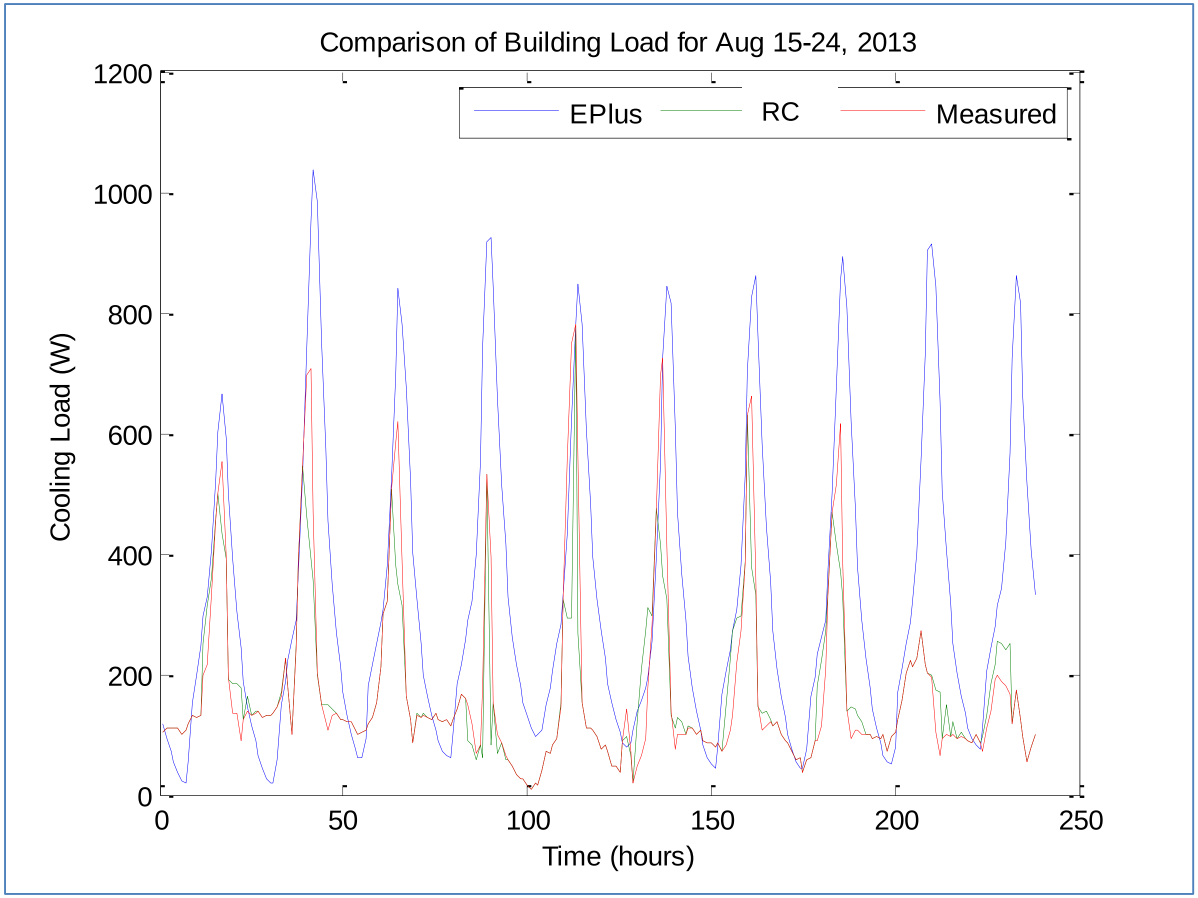
$$C = V = [v_1|\ldots|v_n]\ and\ Av_j = \lambda_j v_j,\ \ j = 1, \ldots, n$$

$$e^{Dt} = \mathrm{diag}\left(e^{\lambda_1 t}, \ldots, e^{\lambda_n t}\right)$$

$$e^{At} = V\left(\mathrm{diag}(e^{\lambda_1 t}, \ldots, e^{\lambda_n t})\right)V^{-1}$$

Research Results: Cooling Load Estimation

1) Development and Validation of Thermal Model for Real-Time Estimation of Building Load: Cooling Season



Research Results: Heating Load Estimation

2) Development and Validation of Thermal Model for Real-Time Estimation of Building Load: Heating Season