Model-Based Systems Engineering for High Performance Building Simulation & Design

Michael Wetter (LBNL)

Clas A. Jacobson (UTRC)

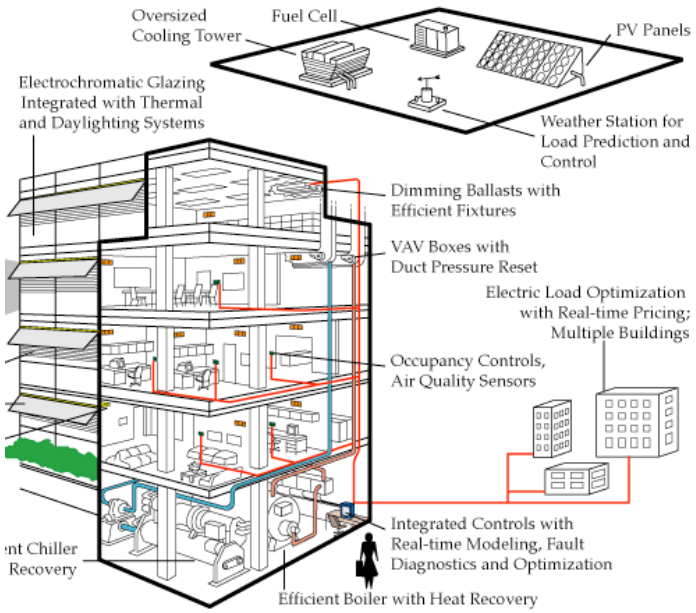
Scott A. Bortoff (UTRC)

Alberto Sangiovanni Vincentelli (UC Berkeley)

December 21, 2007

United Technologies Research Center

NZEB Challenges: Design & Operation

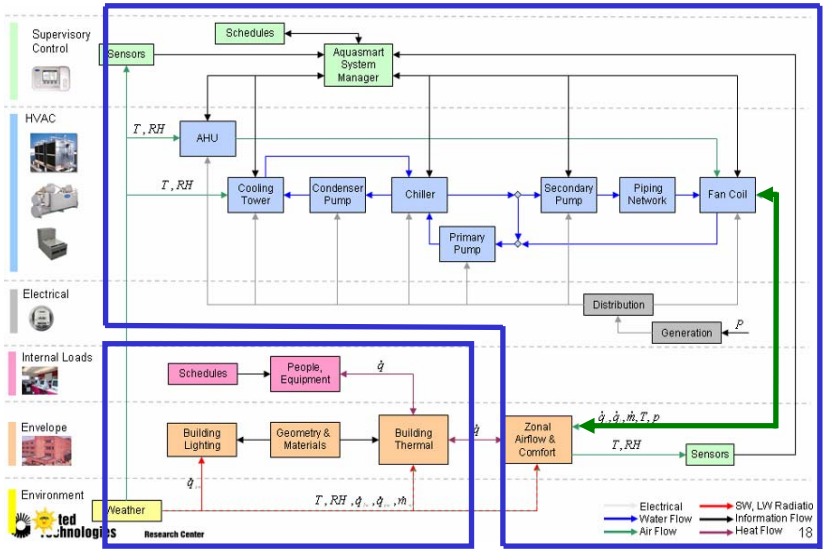


Technologies	Typical SOA Design	"Typical' ZEB Design*
Façade	Sealed Envelope	Hybrid Ventilation
	Passive Façade	Active Façade / Double Skin
	Low Mass	High Mass
	High Performance Glazing	High Performance Glazing
HVAC	Coupled Latent & Sensible	Decoupled Latent & Sensible
	VAV HVAC	Radiant Heating & Cooling
	Mixed	DOA
	Centralized VSD Fan	Decentralized VSD Fans
	No ERV	ERV
	No Desiccants	Desiccants
Lighting	No Daylighting	Daylighting
	Occupancy Sensors	Occupancy Sensors

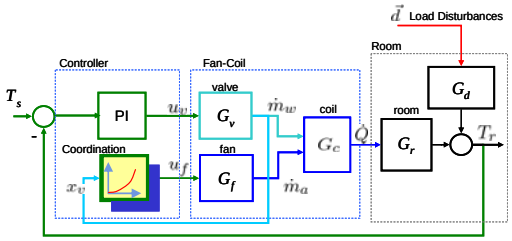
* New Construction: 4-5X Reduction
Retrofits: 30-60% Reduction

Challenges:

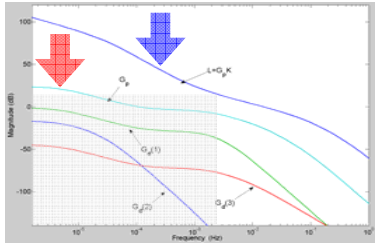
Managing System Interactions



Robust Optimal Controls

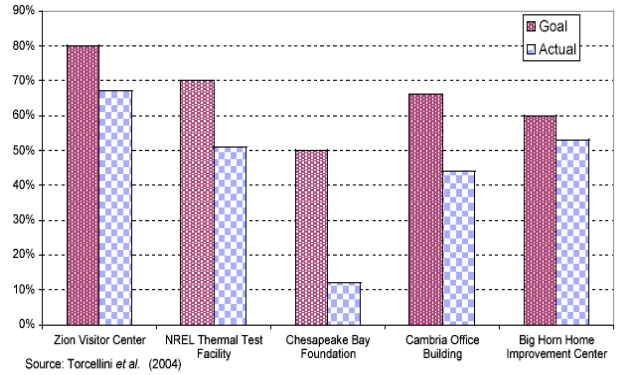


Loop Gain Reduction



Modeling / Actual Performance Gaps

Energy Cost Savings



Source: Torcellini *et al.* (2004)

∞ 0 Sensitivity Increasing

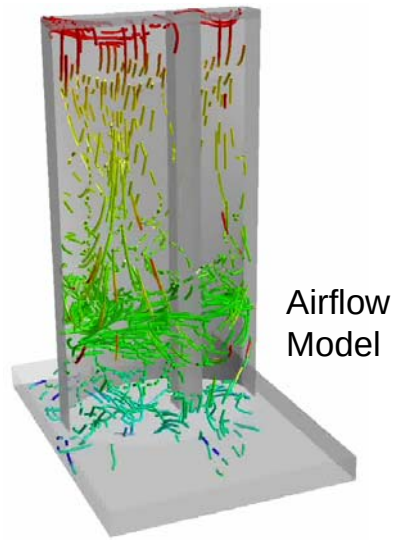
$$C\frac{dT}{dt} = UA(T_\infty - T) + Q_{GAIN}$$

Performance & Complexity Arise from Interactions

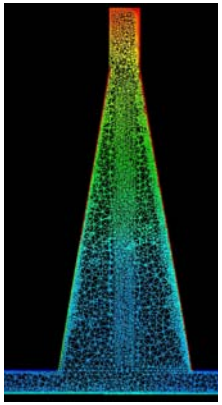
50-Story Hotel

- 30% energy increase over benchmark
- Poor comfort (100F+ at top floors)

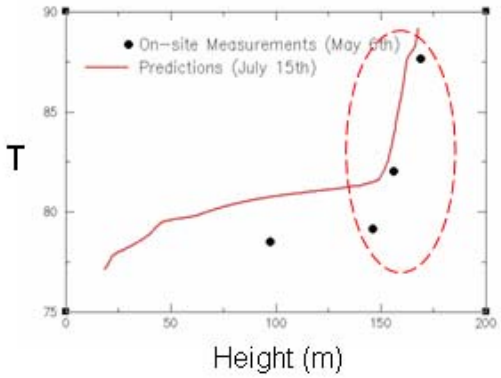
Skylight



Airflow Model



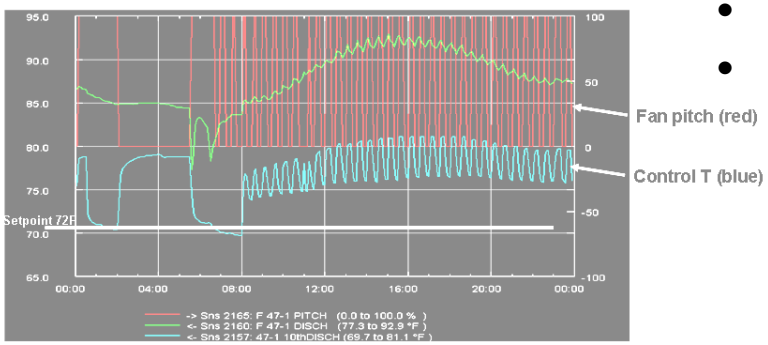
Thermodynamic Model and Validation

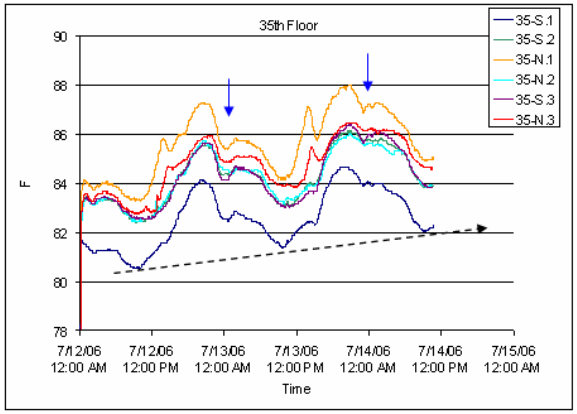


Problems Caused by *interactions* among

- Envelope & Windows
- Thermal Mass
- Airflow
- HVAC Controls
- Smoke Controls

Ineffective Operational Mitigation

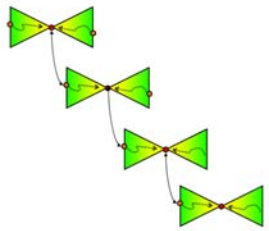


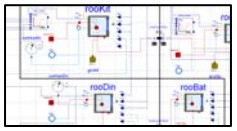


Control Strategy Causes Loss of Control

United Technologies Research Center

Enabling Technologies





Challenges

Managing System Interactions

Concurrent Design Process

Robust Optimal Controls

Model Validation

Maintaining Performance

Enabling Technologies

Object Oriented Encapsulated Modelin

Platform Based Design

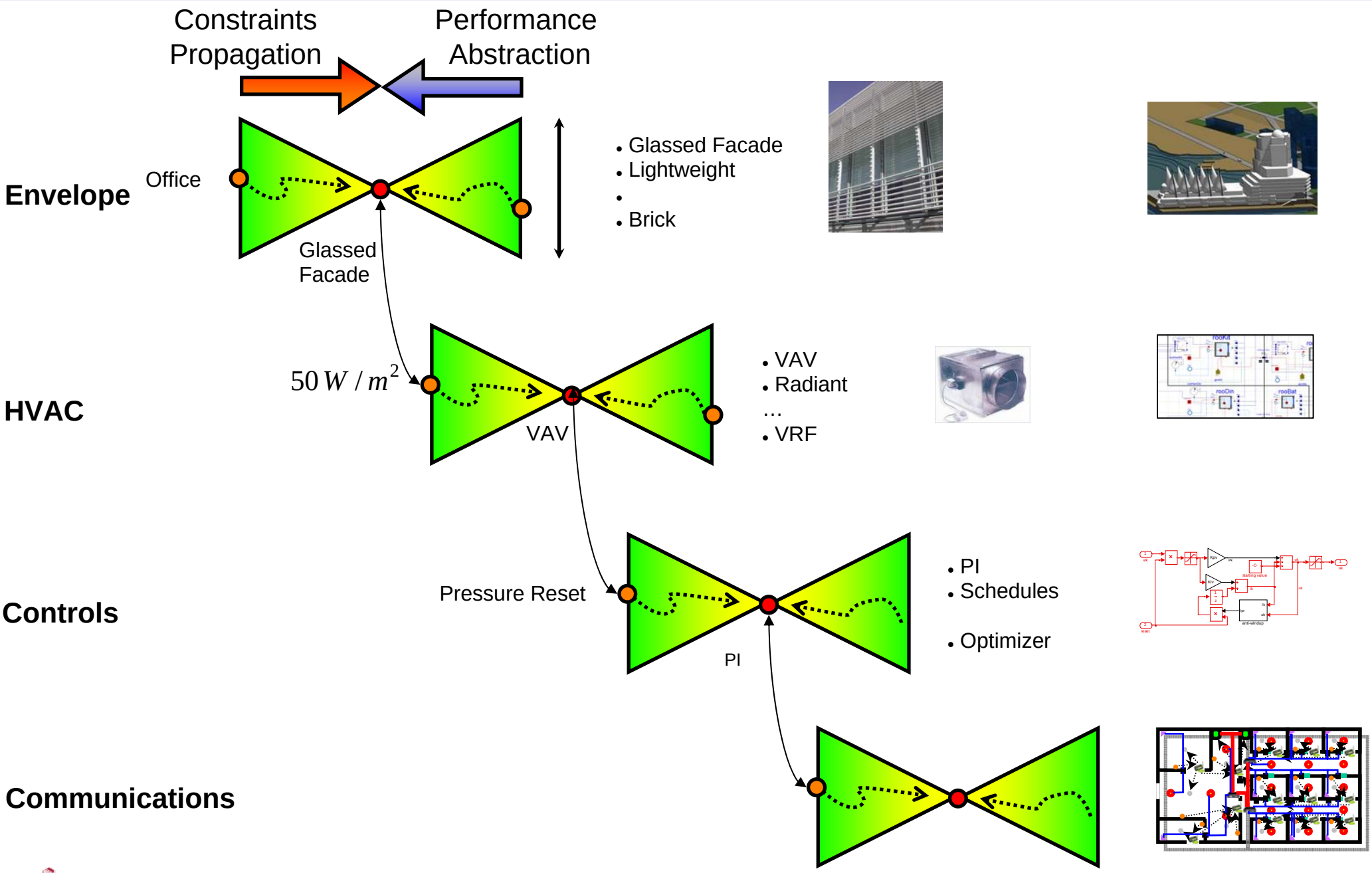
Model-Based Design

Data Assimilation with Inverse

Diagnostics

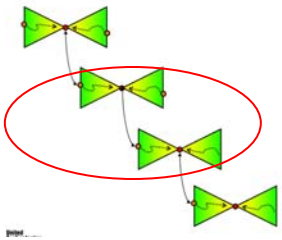
United Technologies Research Center

Platform-Based Design

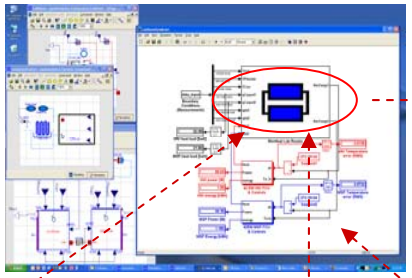


United Technologies Research Center

Object Oriented Modeling

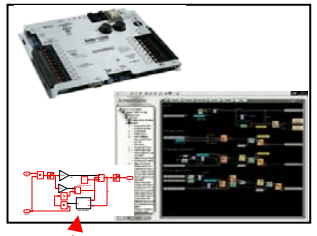


Common Analysis Platform



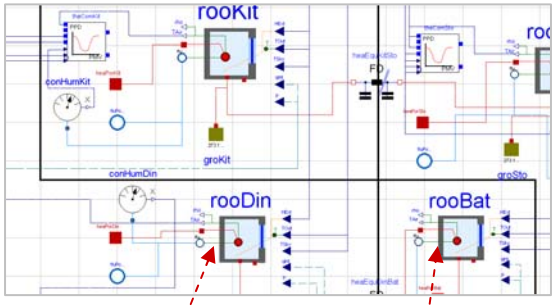
Building + HVAC Executable Model

HIL Verification

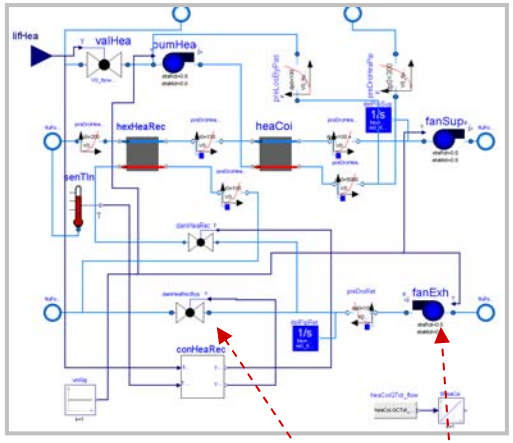


Software Generation

Envelope & Zones

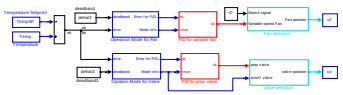


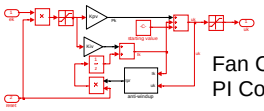
HVAC



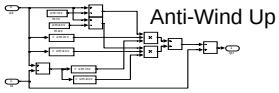
Controls

Hydronic System Control



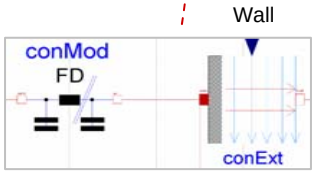


Fan Coil PI Control



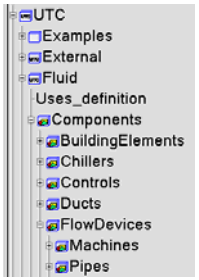
Anti-Wind Up

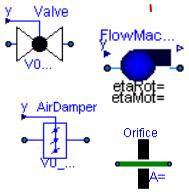
Component Libraries



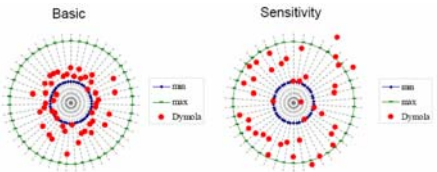

```
// dT/dt computation

cap[1]*der(T[1]) = surInt.Q_flow + q_flow[1];
```





$$\dot{V} = C_d A \sqrt{2/\rho}\, \Delta P^m$$

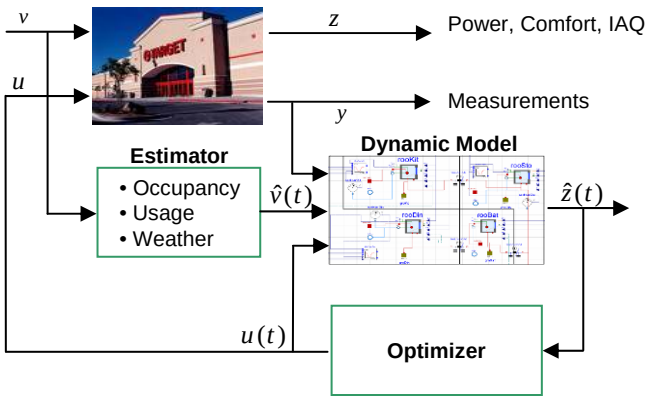


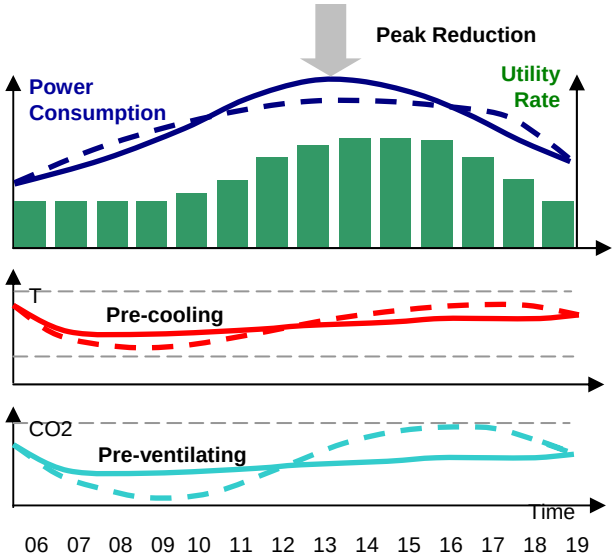
ASHRAE 140 Verfication

Interaction → Common Platform
Complexity → Encapsulation

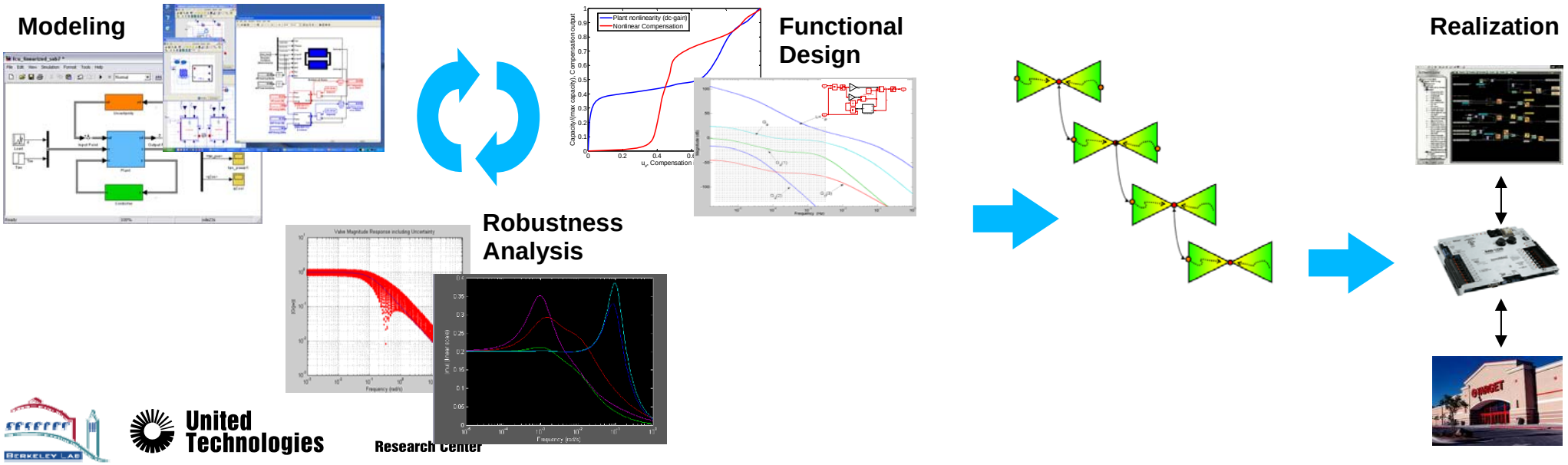
Robust, Optimization Based Controls

Optimizing Algorithms





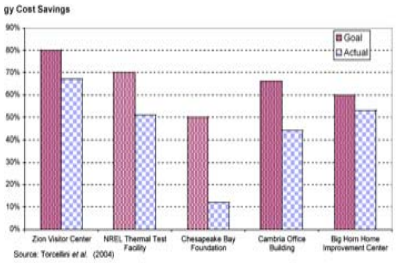
Robust Control Design & Implementation: Methods, Process, Tools



Data Assimilation by Inverse Modeling

"We need to develop better benchmarking of buildings based on their actual energy use."
- Kent W. Peterson, ASHRAE President, Presidential Address, 2007.

Modeling / Performance Gaps



Building

Disturbances

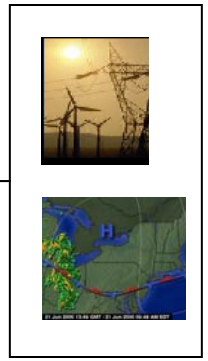
Controls

Performance Variables

Measured Variables

Heterogeneous Sensors

Disturbance Measurements

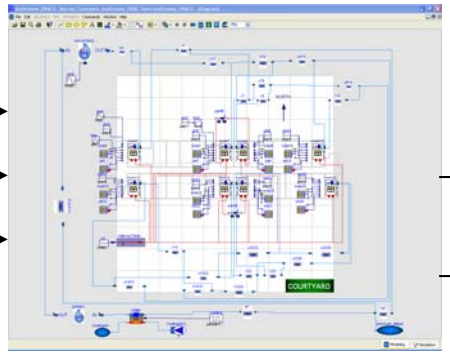


Forward Model

Schedules

Certain Parameters

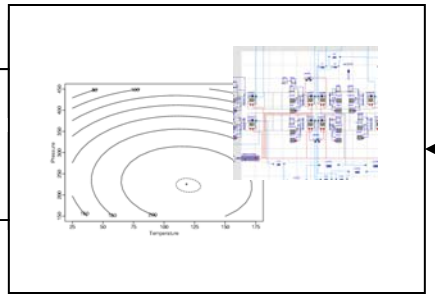
Uncertain Parameters



Virtual Submetering

Calibration

Inverse Model



Residuals

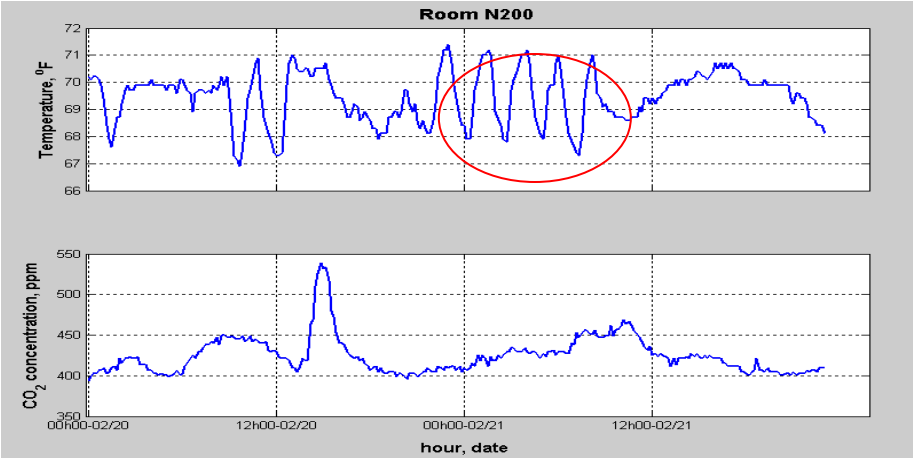
Barriers
- Common Data Formats
- Immature Methodology
- Software Tools

- **Quantify measurement effectiveness**
- **Identify Modeling Gaps**
- **Validate Models**

United Technologies Research Center

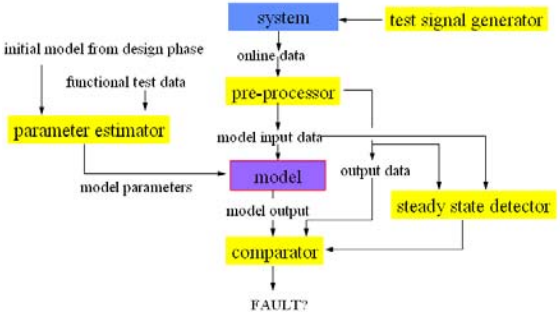
Diagnostics

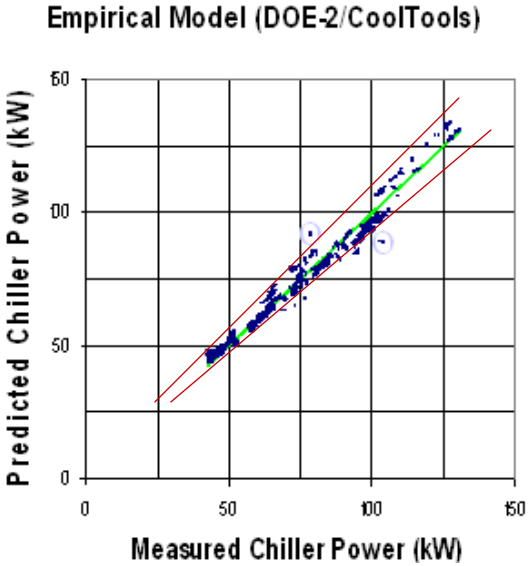
Operational faults waste ~20% energy
- HVAC – air distribution
- Operations and control



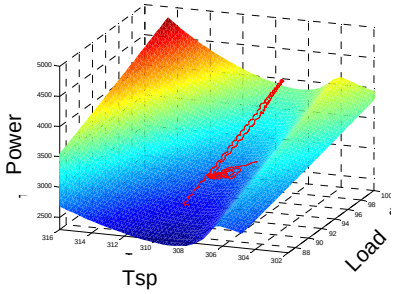
UTRC L-Building BMS

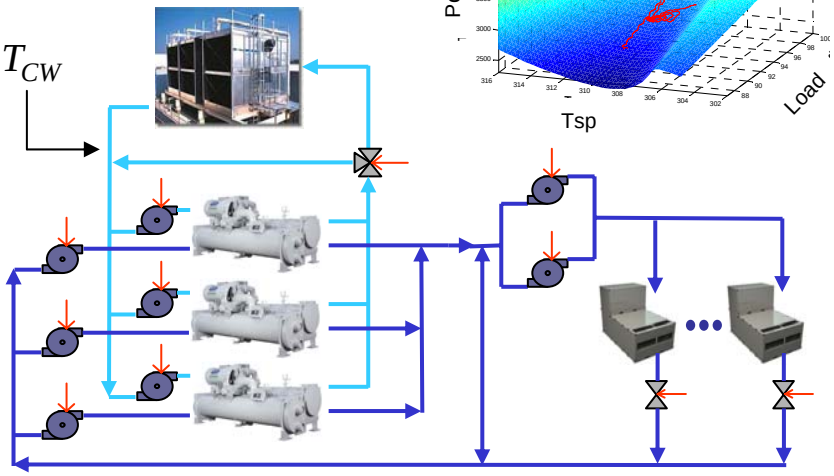
FDD Current State:
- Components & Subsystems
- Steady-State



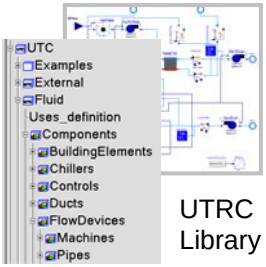


Needs
- System-Level FDD
- Exploit Dynamics





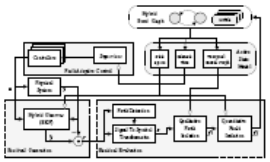
Enablers
- Dynamic Model Library
- Remote Monitoring
- Data Assimilation Methods & Tools
- FDD Methods & Tools e.g. FACTS



UTRC Library

WebCTRL

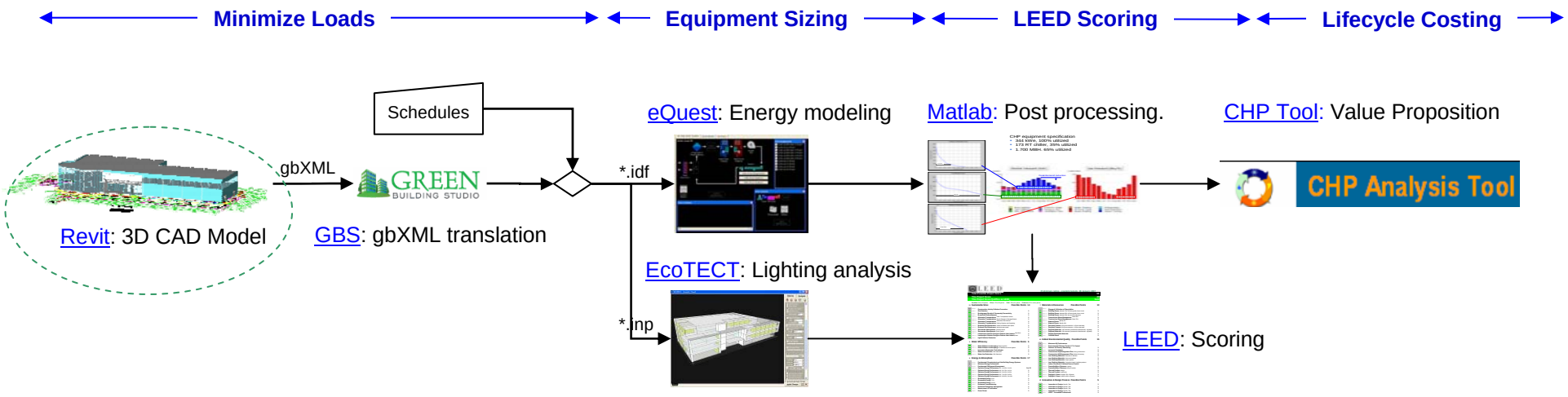
Vanderbilt FACTS



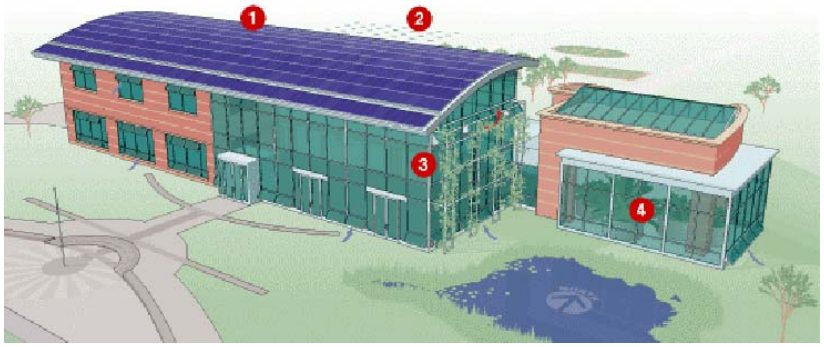
United Technologies Research Center

Backup

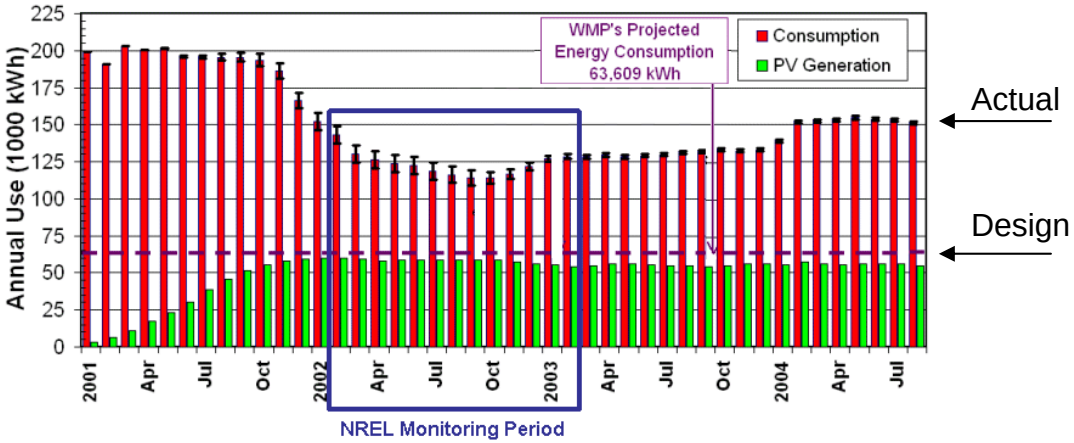
Linear Design Process



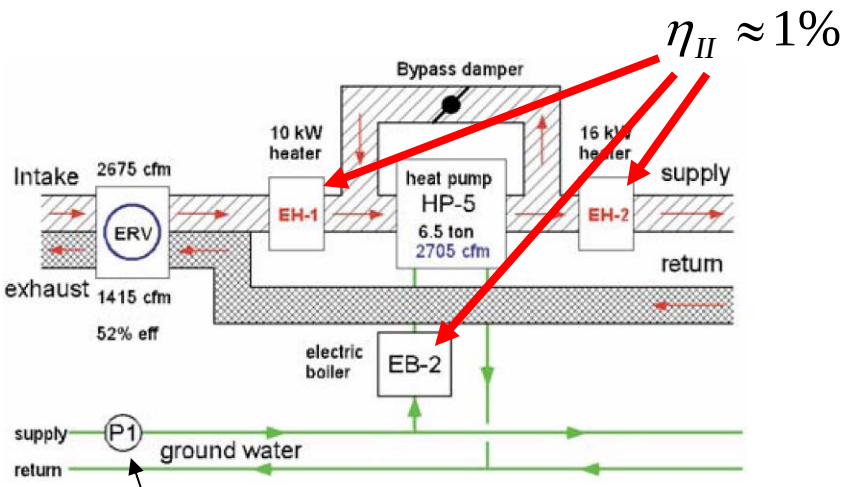
Example: Oberlin College "ZEB"



Performance Gaps



Main Building Air Supply System



Pump P1 runs continuously because no linked to control system.

- "All Electric Building" is second law inefficient.
- Electric boiler feeds radiant system at 66°C, mixed with 49°C for radiant floor.
- Improperly sized heat pumps caused comfort problems.
- EB-2 sent heat to ground in early occupancy. Now off.
- In first 2 operating years, not less source energy use than comparable building type.
- More recently, 3-17% more efficient than similar buildings.

Actual / predicted performance gaps
Ineffective use of models.
Inefficient Control Algorithms.

United Technologies Research Center