Energy Efficient Buildings

Building Control Opportunities & Challenges

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Presentation to EE392N Intelligent Energy Systems

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Team

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Key Points

- Energy and buildings. Importance of sector as building energy efficiency can be realized quickly.

- Current state of building controls.
  - Design & implementation approaches using networked controls, standard control sequences and graphical entry
  - Simple PI controls usually used; overall performance is not optimized

- Energy efficient (high performance) buildings. Achieving >50% over current standards (ASHRAE 90.1) is possible; proof points occur for all sizes and climates; buildings designed using climate responsive design principles and building controls that integrate diverse components and recognize dynamics.

- Gaps in control performance. Delivery process handoffs are a problem and are where there is a loss of potential for energy savings in design, construction and operation.

- Case study: Merced campus control. Recognition of key dynamics, role of modeling and control, presentation of control results to campus operators.
  - Need to capture dynamics (storage and loads), uncertainty (weather), couplings (temporal);
  - Role and fidelity of modeling needed (ability to determine optimal set points for flow rates, temperatures);
  - Actionable information for fault handling (insufficient flow preventing higher COP)

Outline

Energy Usage

Building Controls

High Performance Buildings & Gaps

Case Study: Campus Level

Building Energy Demand Challenge

Buildings consume

- 39% of total U.S. energy
- 71% of U.S. electricity
- 54% of U.S. natural gas

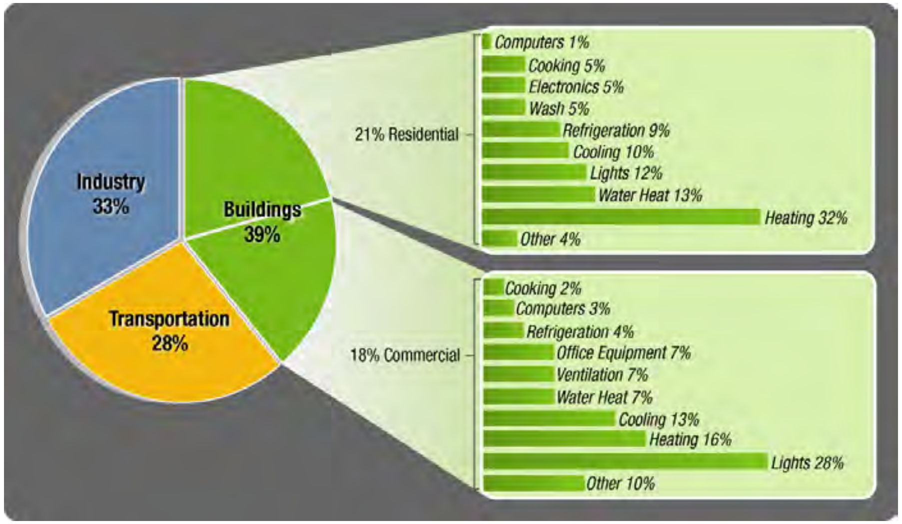
Building produce 48% of U.S. Carbon emissions

Commercial building annual energy bill: $120 billion

The *only* energy end-use sector showing growth in energy intensity

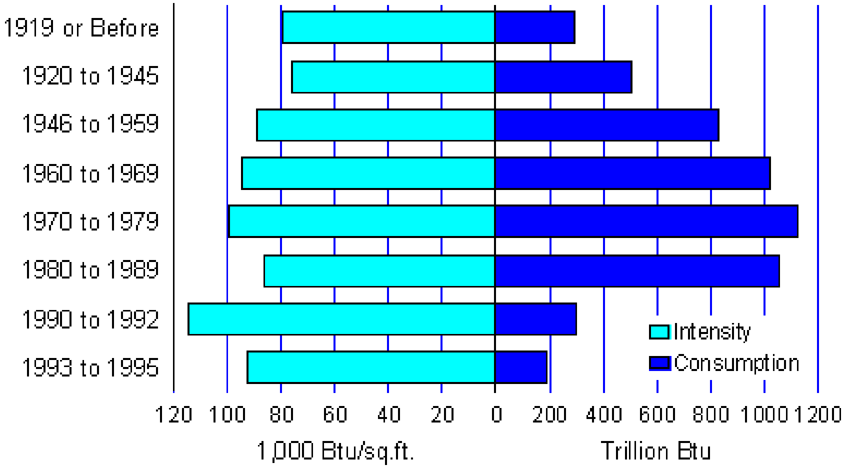
- 17% growth 1985 - 2000
- 1.7% growth projected through 2025

Energy Breakdown by Sector



Sources: Ryan and Nicholls 2004, USGBC, USDOE 2004

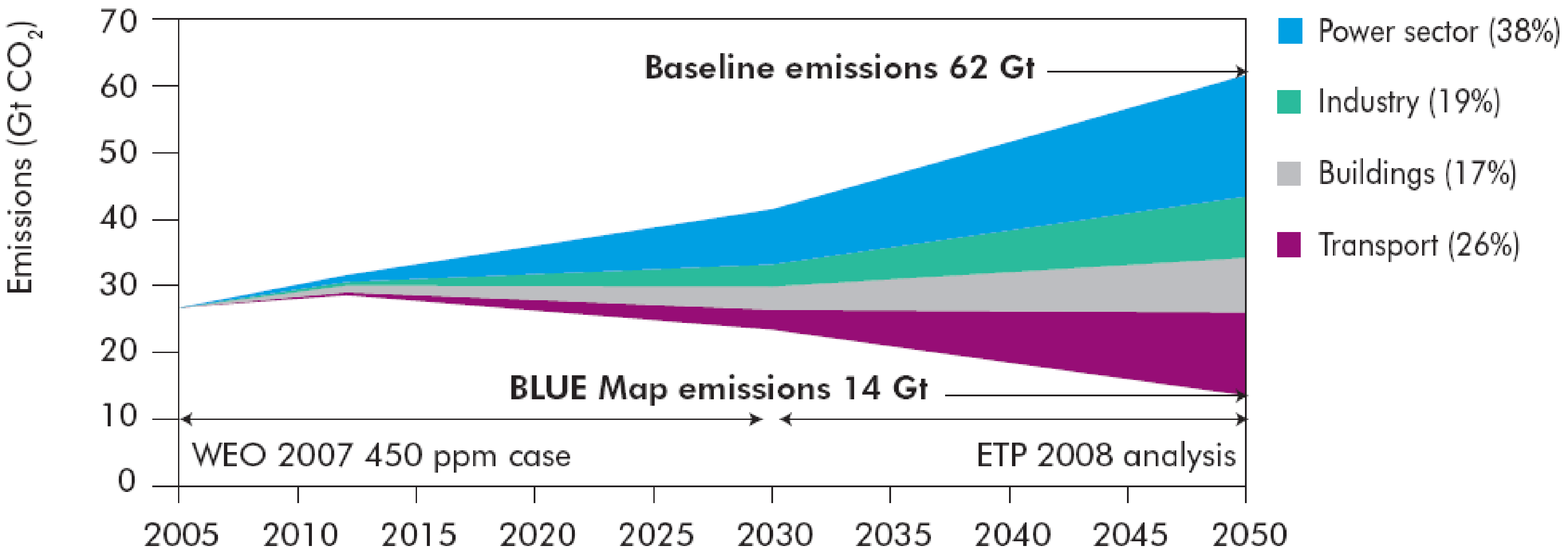
Energy Intensity by Year Constructed



Energy Information Administration
1995 Commercial Buildings Energy Consumption Survey

How Buildings Fit into the Big Picture

IEA Estimates of Emissions Abatement by Source/Sector



Sector	**2050 BAU**	**2050 Blue MAP**	**Reduction**
Power generation	--	--	18.2
Industry	23.2	5.2	9.1
Buildings	20.1	3.1	8.2
Transport	18	5.5	12.5
Total	***62***	***14***	***48***

Source: IEA Energy Technology Perspective 2008

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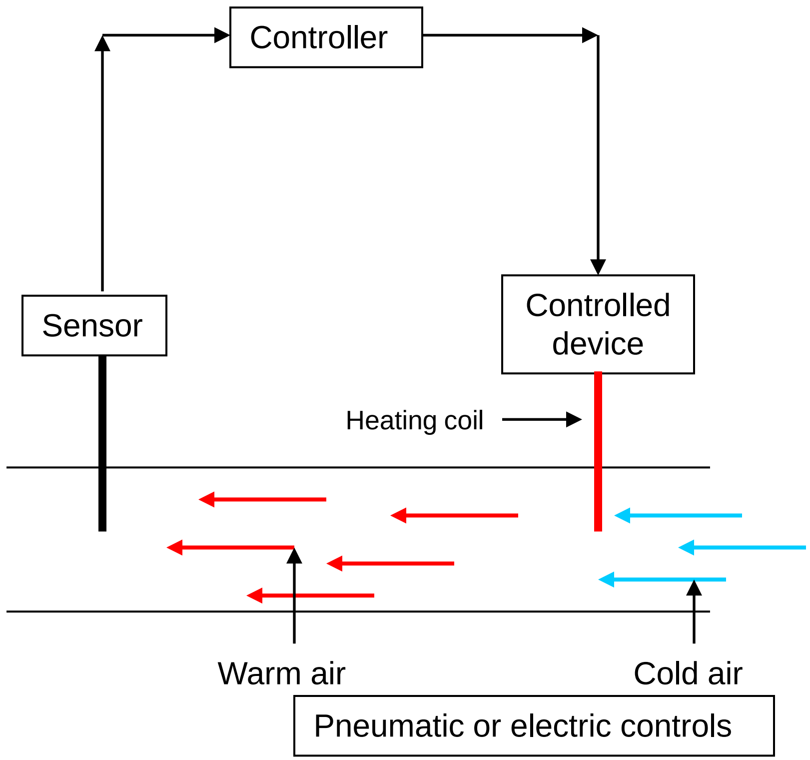
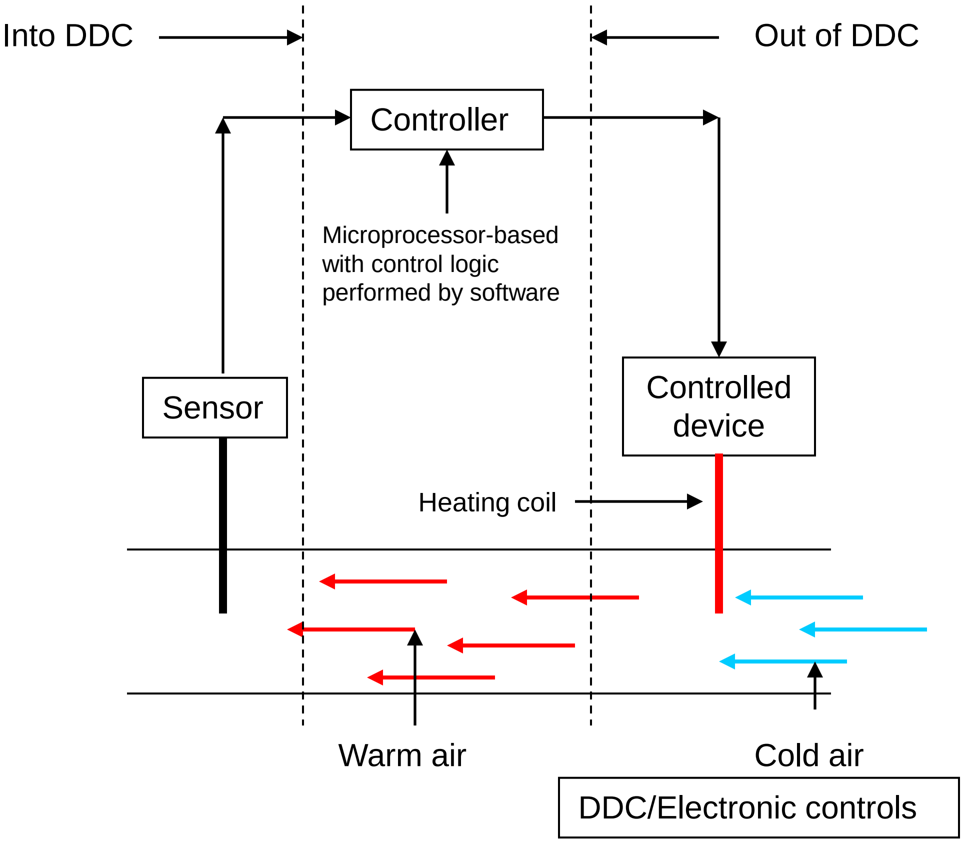
DDC CONTROLS

Types of controls



Pneumatic or electric controls



DDC/Electronic controls

<u>What is control?</u>

The process of controlling an HVAC system involves three steps

These steps include first measuring data, then processing the data with other information and finally causing a control action

The controller processes data that is input from the sensor, applies the logic of control and causes an output action to be generated

Source: DDC Online, www.ddc-online.org

<u>Definition of Direct Digital Control</u>

DDC control consists of microprocessor-based controllers with the control logic performed by software

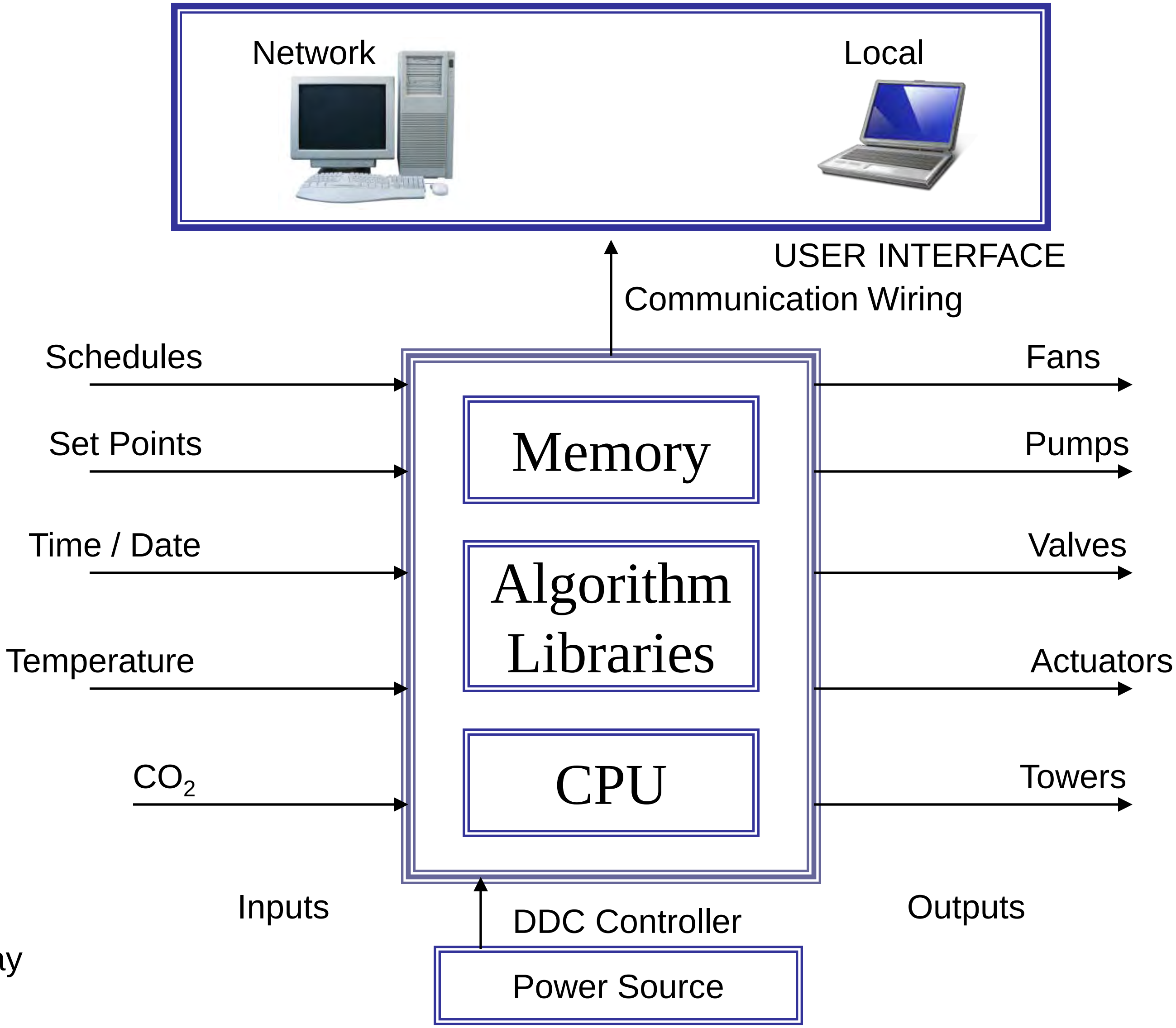
<u>Benefits of DDC over Pneumatic/Electric</u>

The benefits of direct digital control over other technologies is that it improves the control effectiveness and increases the control efficiency

The three main direct benefits are improved effectiveness, operation efficiency and energy efficiency

BUILDING SOLUTION

DDC controls system elements



Network

Local

USER INTERFACE

Communication Wiring

Schedules

Set Points

Time / Date

Temperature

CO_2

Inputs

Memory

Algorithm Libraries

CPU

DDC Controller

Power Source

Fans

Pumps

Valves

Actuators

Towers

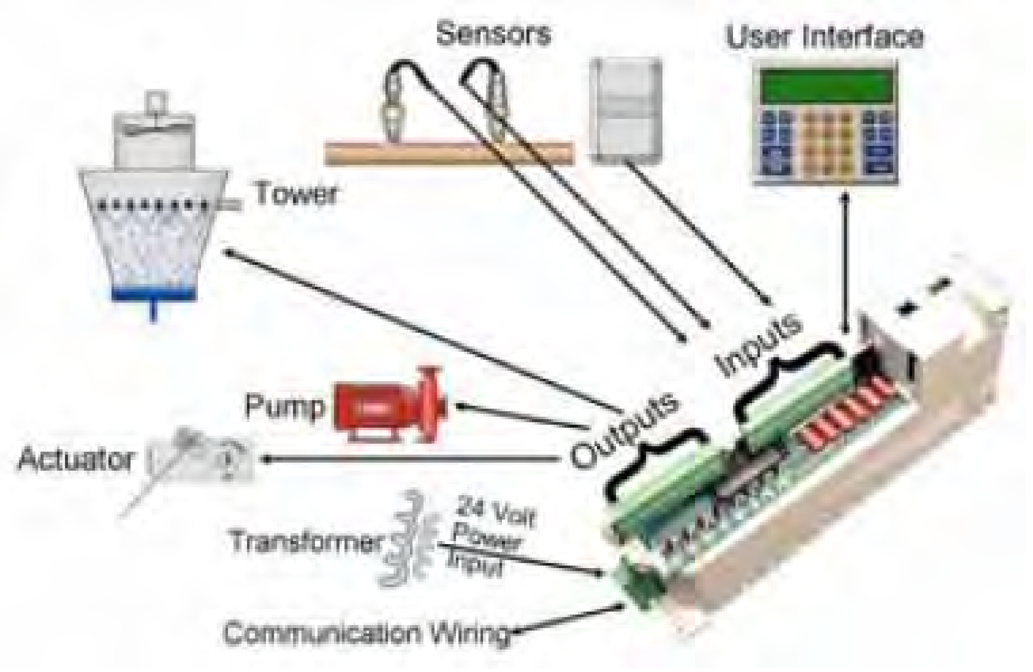
Outputs

Define: a. Gateway
b. Router

DDC CONTROLS

Applications and characteristics

General purpose DDC controller usage



A general purpose DDC controller would include an air handler with a supply fan, dampers, heating and cooling coils, and filter section

Another application for DDC controllers is the retrofit of HVAC equipment or systems in existing buildings

Their applications can be extended beyond their traditional functions by integrating lighting and security systems

DDC CONTROLS

DDC management systems

In the beginning, the primary function of HVAC systems was the temperature regulation of the conditioned space

As technology has advanced, the microprocessor inside DDC controls has been tapped to host additional benefits and capabilities

The use of DDC allows the management of four key areas:

Comfort management: temperature, humidity, ventilation, and air volume are now controlled more precisely

Energy management: systems can be started and stopped based on the most energy-efficient time of operations

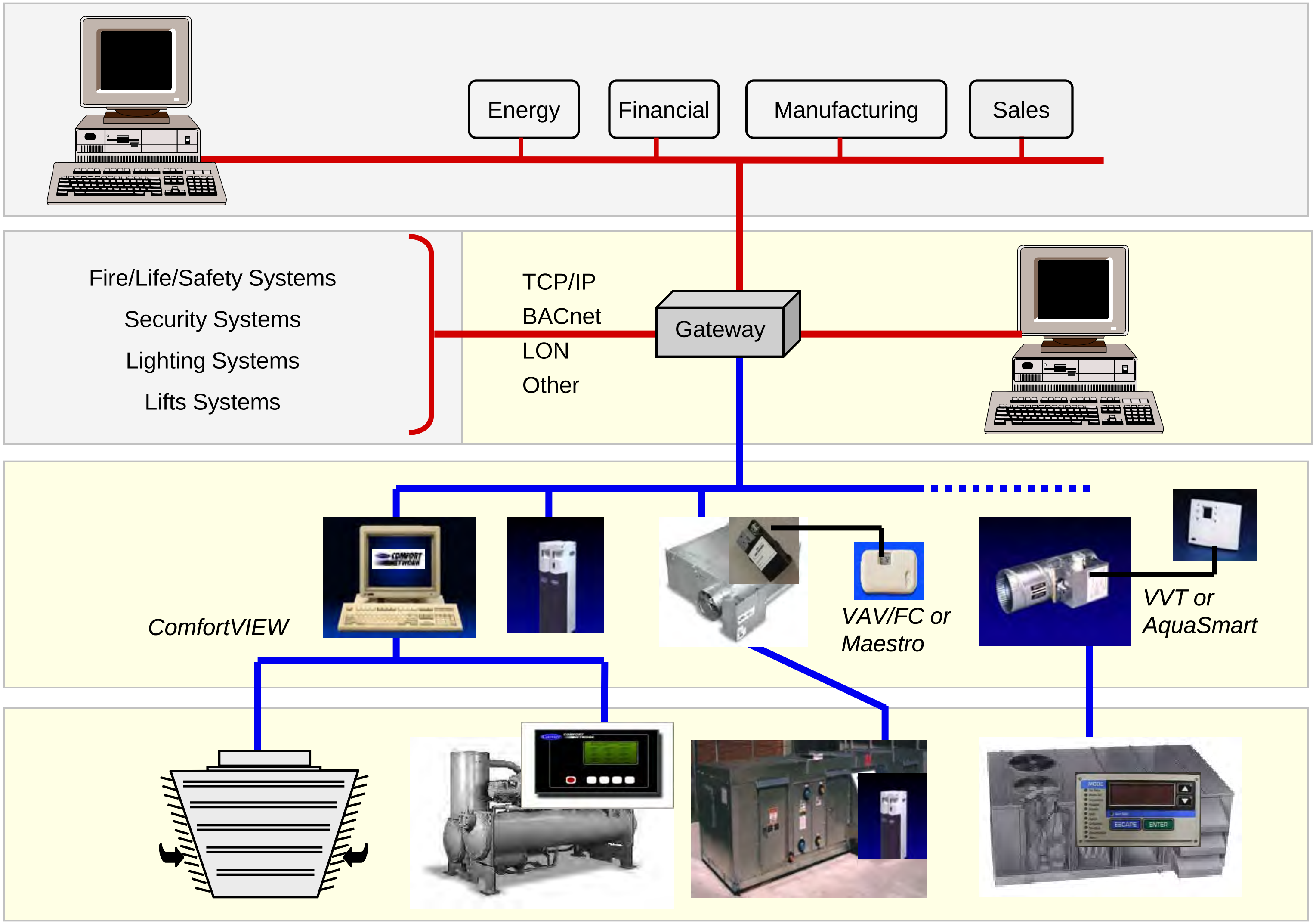
Maintenance management: DDC microprocessors can produce huge quantities of data which can be used to determine better system operations (alarm, trending reports…)

Information management: energy usage of various components and rooms

Four key management systems

BUILDING SOLUTION

Building controls hierarchy



Enterprise Level

Energy

Financial

Manufacturing

Sales

Building Level (BMS)

Fire/Life/Safety Systems

Security Systems

Lighting Systems

Lifts Systems

TCP/IP

BACnet

LON

Other

Gateway

HVAC Control Systems

Network

Controls

Interface

Components

ComfortVIEW

VAV/FC or Maestro

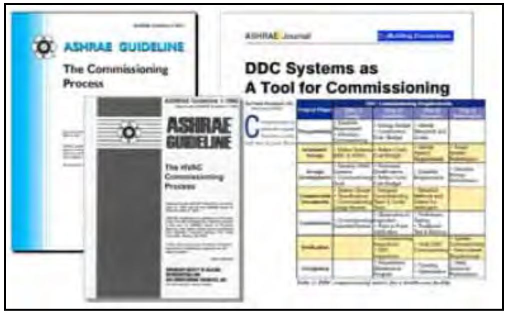
VVT or AquaSmart

Equipment and Equipment Controls

Direct Digital Controls (DDC)

Specification and installation

Specification → Installation → Startup → Commissioning → Building occupation


ASHRAE GUIDELINE

The Commissioning Process

ASHRAE GUIDELINE

The HVAC Commissioning Process

ASHRAE Journal

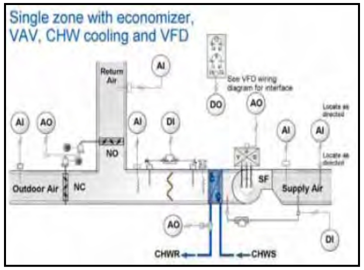
DDC Systems as A Tool for Commissioning

General

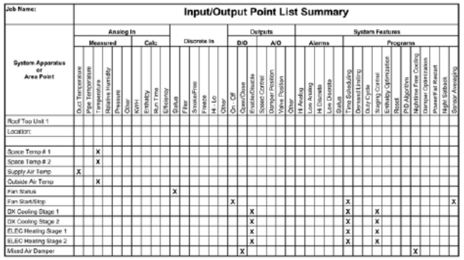
Products

Execution

→ Sequences of operation



System diagram

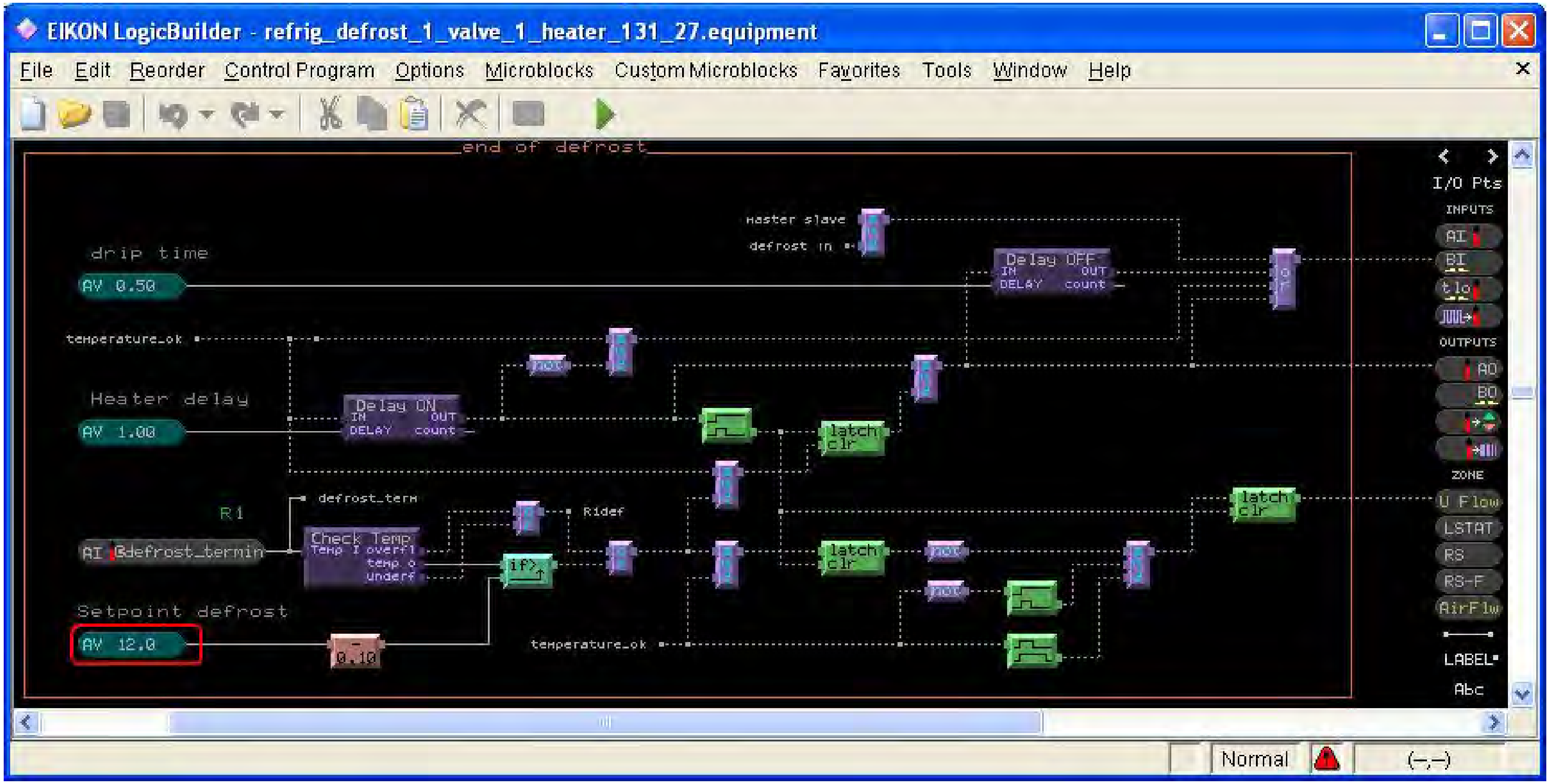


Job Name:	Input/Output Point List Summary																																							
System Apparatus or Area Point	Analog In										Discrete In						Outputs							System Features																
	Measured						Calc										D/O			A/O				Alarms					Programs											
	Duct Temperature	Pipe Temperature	Temperature	Relative Humidity	Pressure	Other	KWH	Enthalpy	Run Time	Efficiency	Status	Filter	Smoke/Fire	Freeze	Hi - Lo	Other	On - Off	Open/Close	Enable/Disable	Speed Control	Damper Position	Valve Position	Other	Hi Analog	Low Analog	Hi Discrete	Low Discrete	Status	Time Scheduling	Demand Limiting	Duty Cycle	Staging Control	Enthalpy Optimization	Reset	PID Algorithm	Nighttime Free Cooling	Damper Optimization	Power/Fail Restart	Night Setback	Sensor Averaging
Roof Top Unit 1																																								
Location:																																								
Space Temp # 1			X																																					
Space Temp # 2			X																																					
Supply Air Temp	X																																							
Outside Air Temp			X																																					
Fan Status											X																													
Fan Start/Stop																	X												X											X
DX Cooling Stage 1																			X										X			X								
DX Cooling Stage 2																			X										X			X								
ELEC Heating Stage 1																			X										X			X								
ELEC Heating Stage 2																			X										X			X								
Mixed Air Damper																		X																		X				

Points list

ALC CONTROLS PLATFORM

Design control algorithms



Outline

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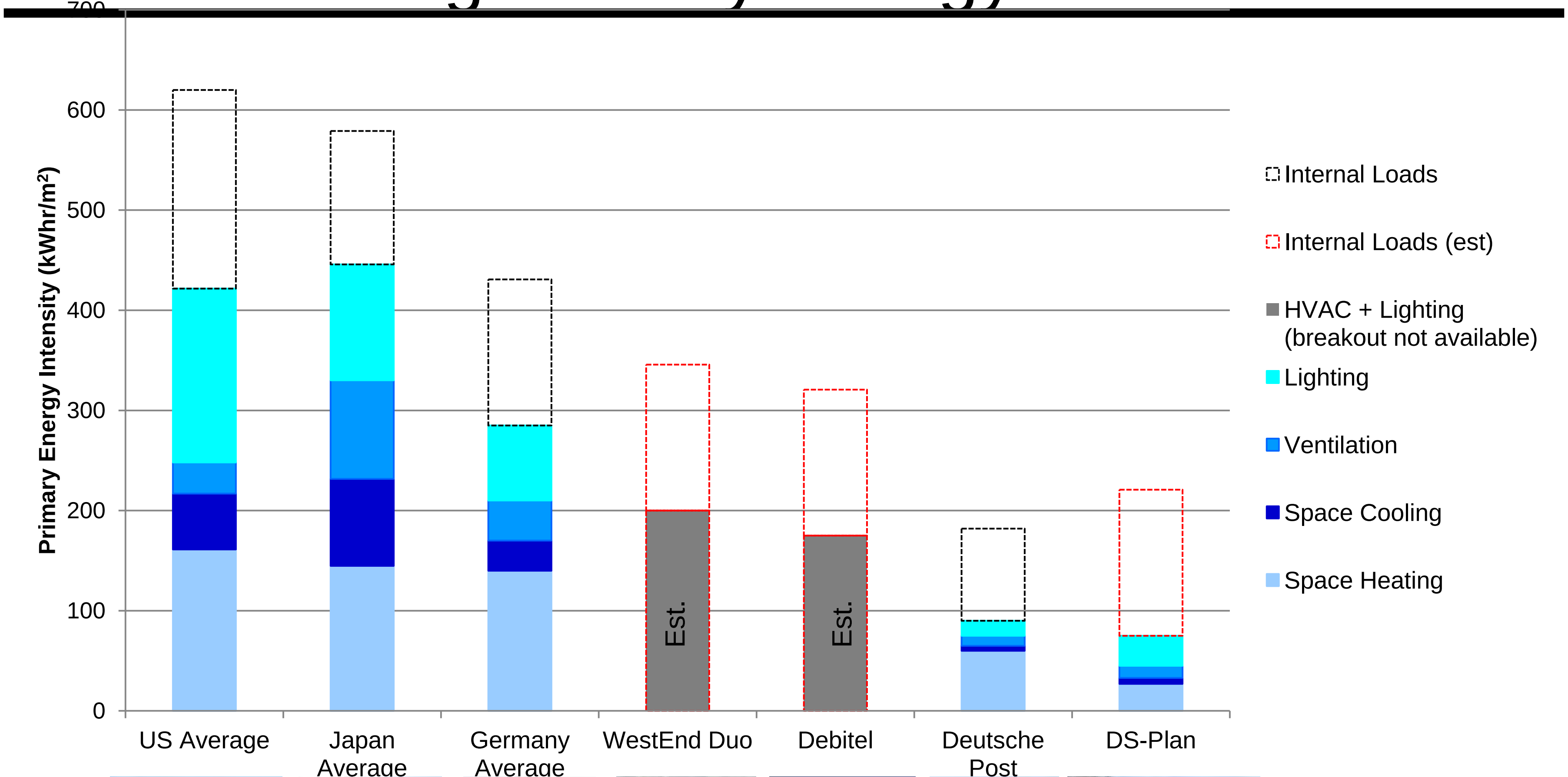
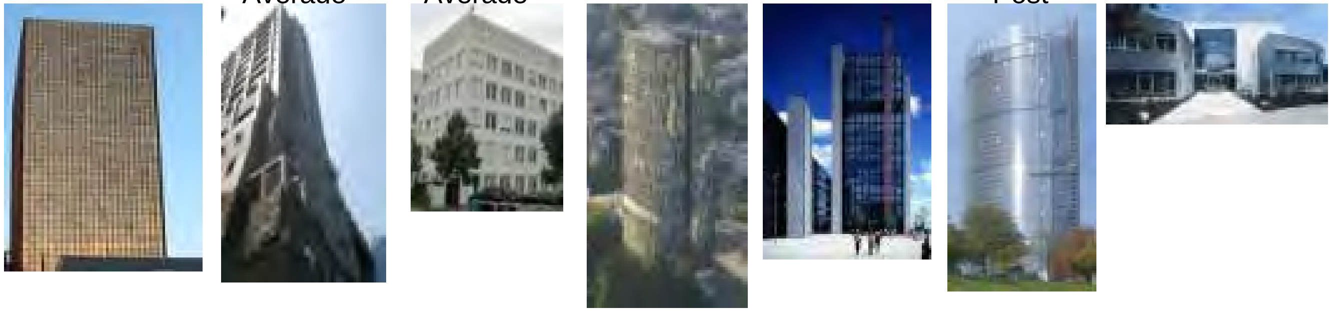
High Performance Buildings & Gaps

Case Study: Campus Level

Office Building Primary Energy Intensities





HIGHLY EFFICIENT BUILDINGS EXIST

Energy Retrofit
10-30% Reduction

Cityfront Sheraton
Chicago IL
1.2M ft^2, 300 kWhr/m^2
5753 HDD, 3391 CDD
VS chiller, VFD fans, VFD pumps
Condensing boilers & DHW

Very Low Energy
>50% Reduction

Bonn Germany
1M ft^2, 75 kWhr/m^2
6331 HDD, 1820 CDD
No fans or Ducts
Slab cooling
Façade preheat
Night cool

LEED Design
20-50% Reduction

Tulane Lavin Bernie
New Orleans LA
150K ft^2, 150 kWhr/m^2
1513 HDD, 6910 CDD
Porous Radiant Ceiling, Humidity Control
Zoning, Efficient Lighting, Shading

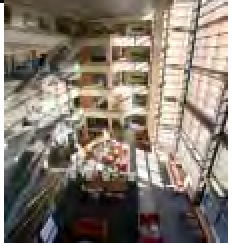
- Different types of equipment for space conditioning & ventilation
- Increasing design integration of subsystems & control

Energy Efficiency Equipment Differences

Current: HVAC Accommodation of Climate

- Lighting cooled by HVAC

- Solar gain cooled by HVAC



- Ventilation latent heat cooled by HVAC

- Ignore local climate: RTU/VAV/Chillers cooling

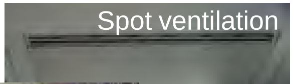
- Ignore local climate: forced air ventilation

Energy Efficient: Climate Responsive

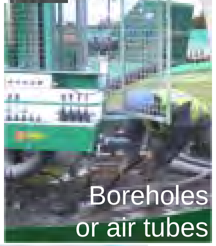
- Decouple lighting from HVAC

- Decouple solar gain from sensible heat gain

- Decouple ventilation latent heat gain



- Leverage local climate: geothermal

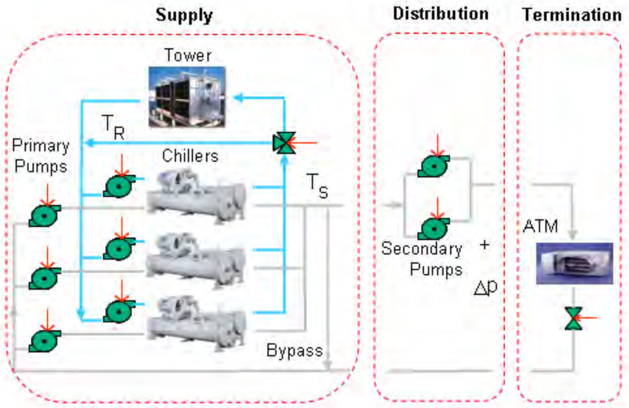


- Leverage local climate: natural ventilation & stack effect

Components → ***Engineered Systems***

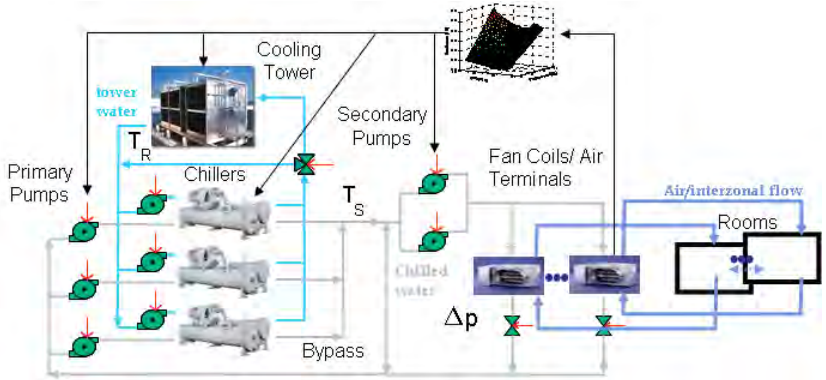
Energy Efficiency Controls Differences

Current: Local Loop Reactive Controls Central Plant Scheduling



Decoupled Architecture & Controls

- Constant T_s → decouples supply from distribution
- Constant Δp → decouples distribution from termination

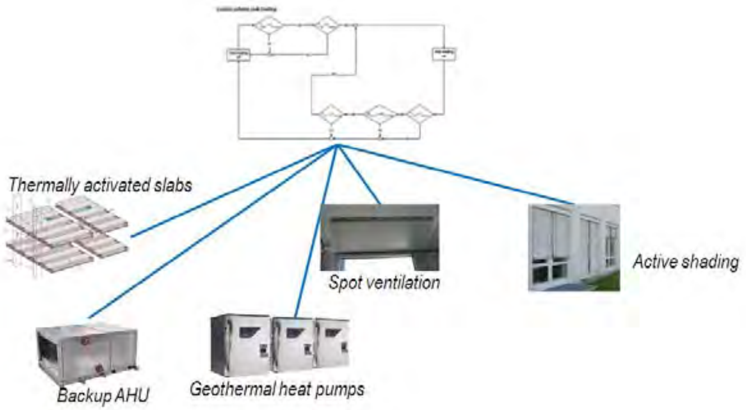


Integrated Architecture & Controls

- Raise T_s to zonal humidity constraint
- Lower Δp to ATM valve constraint
- Peak-seeking for T_R
- Lower primary pump to bypass constraint

Stronger Coupling ⇒ Performance Fragility

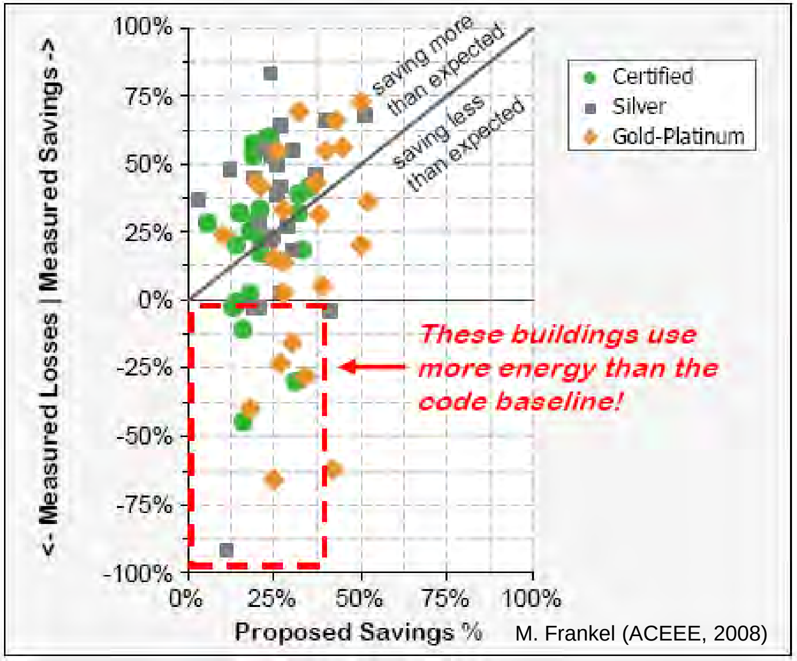
Energy Efficient: Coordinated & Predictive Controls



- **Temperature control**
  - Slab: MPC given 18 hour / degree time constant
  - Local fine-tuning: local heat/AC add & operable windows
- Ventilation
  - Night purge: daily event
  - Buoyancy modes: tight envelope and flow
- **Heat and Cooling Sources**
  - Geothermal: circulating mode, heat pump mode, AC mode
  - Solar gain: outdoor shading
- **Lighting**
  - Daylighting: diffuse light shelves and tubes

Intrinsically Robust Performance

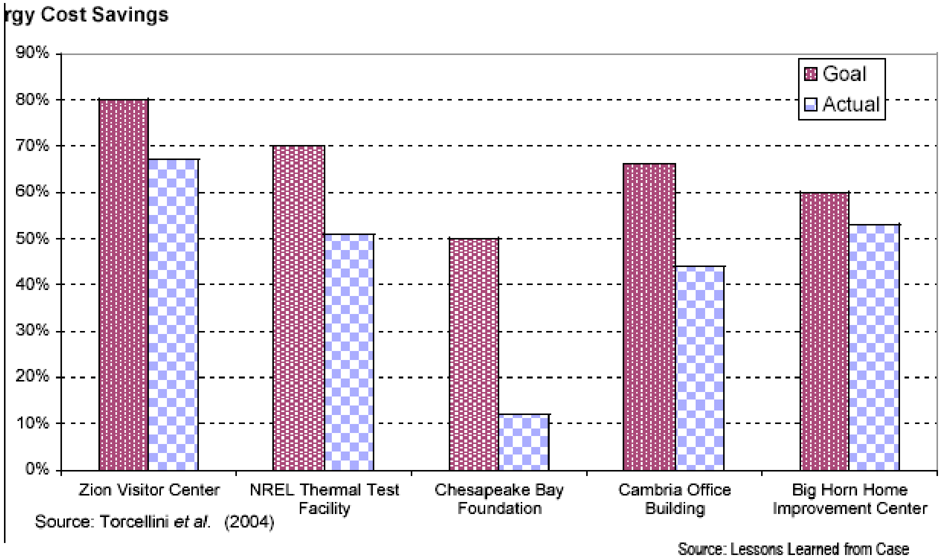
Energy Efficient Buildings: Reality



These buildings use more energy than the code baseline!

M. Frankel (ACEEE, 2008)

Designs over-predict gains by ~20-30%



Source: Torcellini *et al.* (2004)

Source: Lessons Learned from Case Studies of Six High-Performance Buildings, P. Torcellini, S. Pless, M. Deru, B. Griffith, N. Long, R. Judkoff, 2006, NREL Technical Report.

Large Variability in Performance Predictions

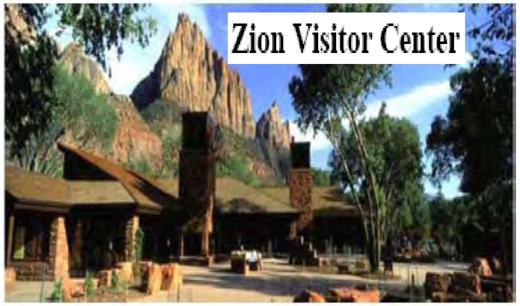
- Performance simulations conducted for peak conditions
- As-built specifications differ from design intent, resulting in compromise of energy performance due to detrimental sub-system interactions
- Uncertainty in operating environment and loads

HIGH PERFORMANCE BUILDINGS: REALITY

Design Intent: 66% (ASHRAE 90.1); Measured 44%

Actual energy performance lower than predictions

The weak point in realizing low energy is not necessarily in the technologies, but rather in the lack of a widely used and cost-effective design and construction processes that can integrate these technologies from a systems engineering perspective. This process includes integrating the technologies with advanced control hardware and control sequences. The final step in the whole building design process includes verifying postoccupancy performance so the building operates as designed. The probability that a low-energy building will be achieved is improved by adopting the whole-building design process.



Design Intent: 80% (ASHRAE 90.1); Measured 67%

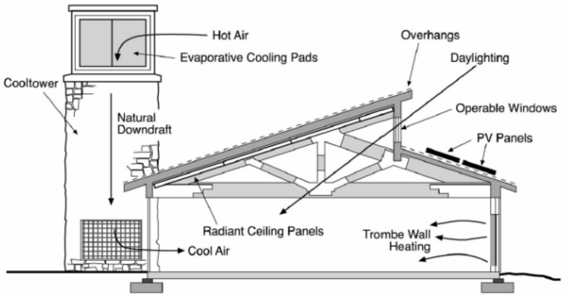


Figure 3-28 Illustration of how the cooltowers work at the Zion Visitor Center

Source: Lessons Learned from Case Studies of Six High-Performance Buildings, P. Torcellini, S. Pless, M. Deru, B. Griffith, N. Long, R. Judkoff, 2006, NREL Technical Report.

NREL National Renewable Energy Laboratory

Lessons Learned from
Case Studies of Six
High-Performance Buildings

P. Torcellini, S. Pless, M. Deru, B. Griffith,
N. Long, and R. Judkoff

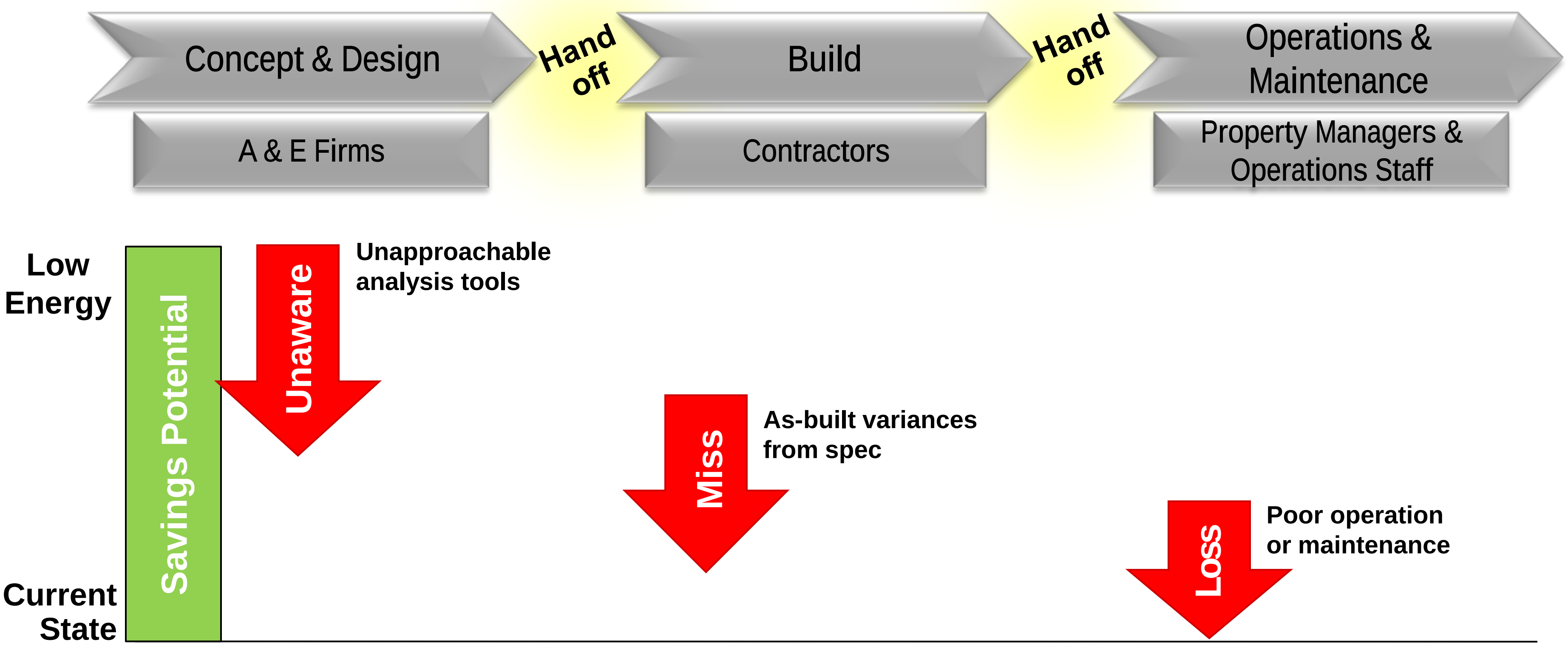
Technical Report
NREL/TP-550-37542
June 2006

Failure Modes Arising from Detrimental Sub-system Interactions

- Changes made to envelope to improve structural integrity diminished integrity of thermal envelope
- Adverse system effects due to coupling of modified sub-systems:
  - changes in orientation and increased glass on façade affects solar heat gain
  - indoor spaces relocated relative to cooling plant affects distribution system energy

Lack of visibility of equipment status/operation, large uncertainty in loads leads to excess energy use

What is Hard: Products, Services and Delivery?



Concept & Design

A & E Firms

Hand off

Build

Contractors

Hand off

Operations & Maintenance

Property Managers & Operations Staff

Low Energy

Current State

Savings Potential

Unaware

Unapproachable analysis tools

Miss

As-built variances from spec

Loss

Poor operation or maintenance

Barrier: Scalability

- Climate specific
- Multiple subsystems
- Dynamic energy flows

Implication on Cost

- Hardware/process for calibration

Implication on Risk

- No Design ProCert/quality process

Barrier: Robustness

- Unknown sensitivities
- No supervisory control

Implication on Cost

- No ProCert process/quality process
- Commissioning costs/process

Implication on Risk

- Control of design in handoffs

Barrier: Productivity

- No diagnostics/guaranteed performance without consulting

Implication on Cost

- Measurement costs
- Recommissioning costs

Implication on Risk

- Facility operations skillsets
- Unbounded costs to ensure performance

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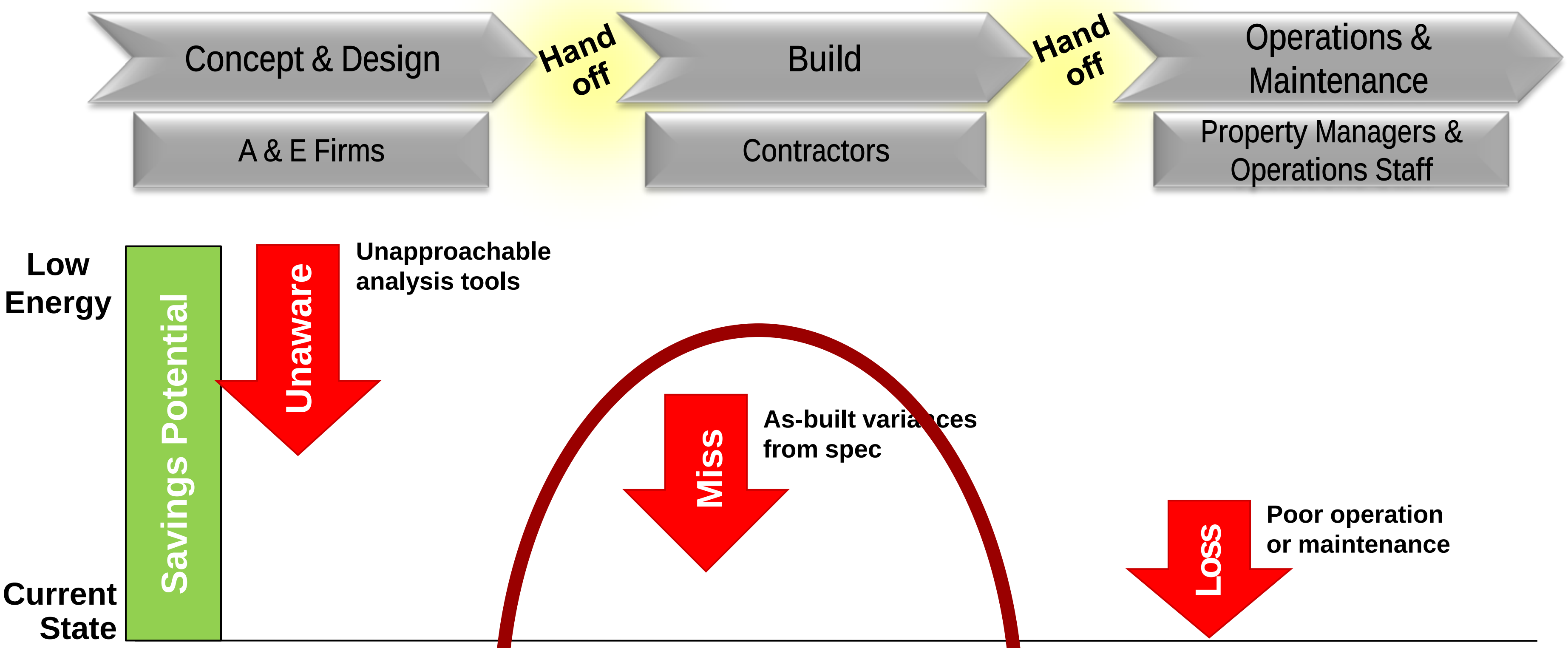

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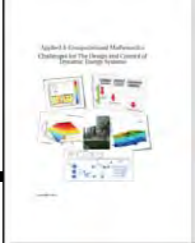
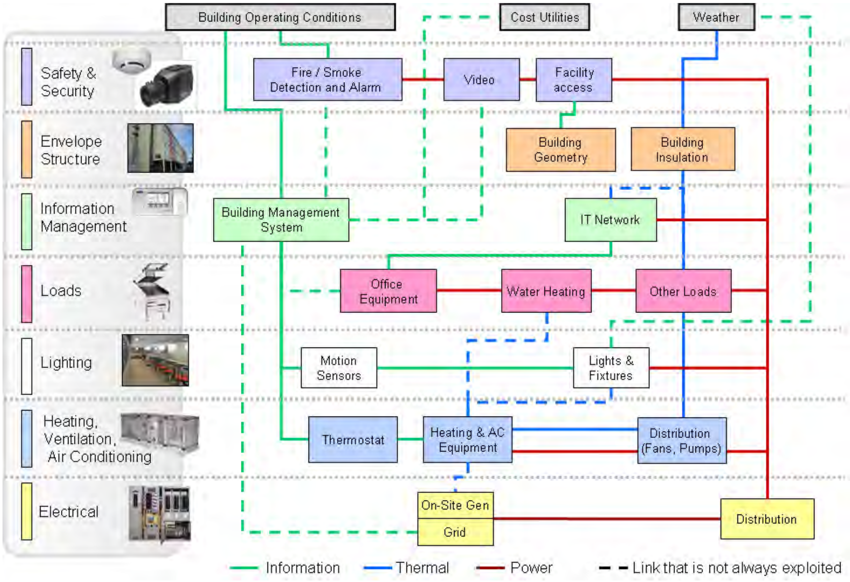
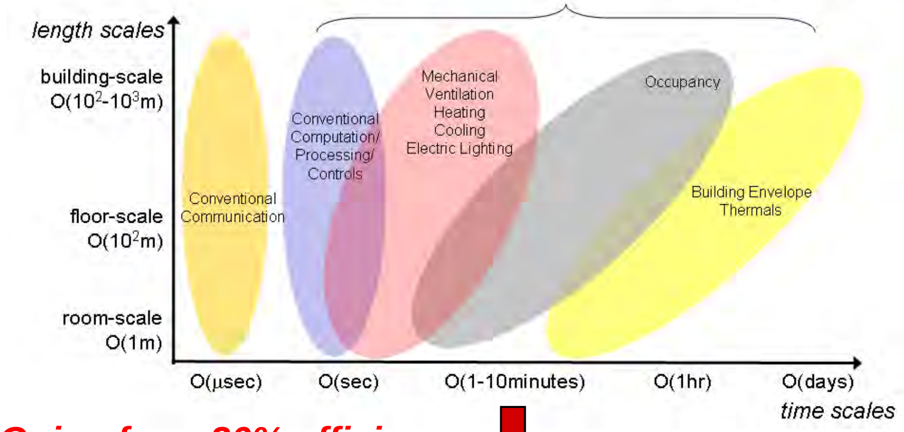
Complexity* in Building Systems



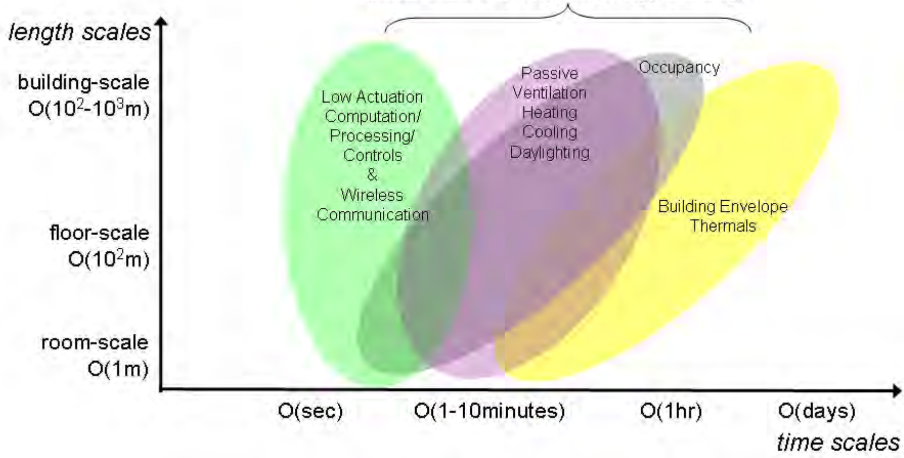


Time scale separation in current building systems and controls



Going from 30% efficiency to 70-80% efficiency

Tightly coupled dynamics over broad range of spatial scales for very low energy buildings



- Components do not have mathematically similar structures and involve different scales in time or space;
- The number of components are large/enormous
- Components are connected in several ways, most often nonlinearly and/or via a network. Local and system wide phenomena depend on each other in complicated ways
- Overall system behavior can be difficult to predict from behavior of individual components. Overall system behavior may evolve qualitatively differently, displaying great sensitivity to small perturbations at any stage

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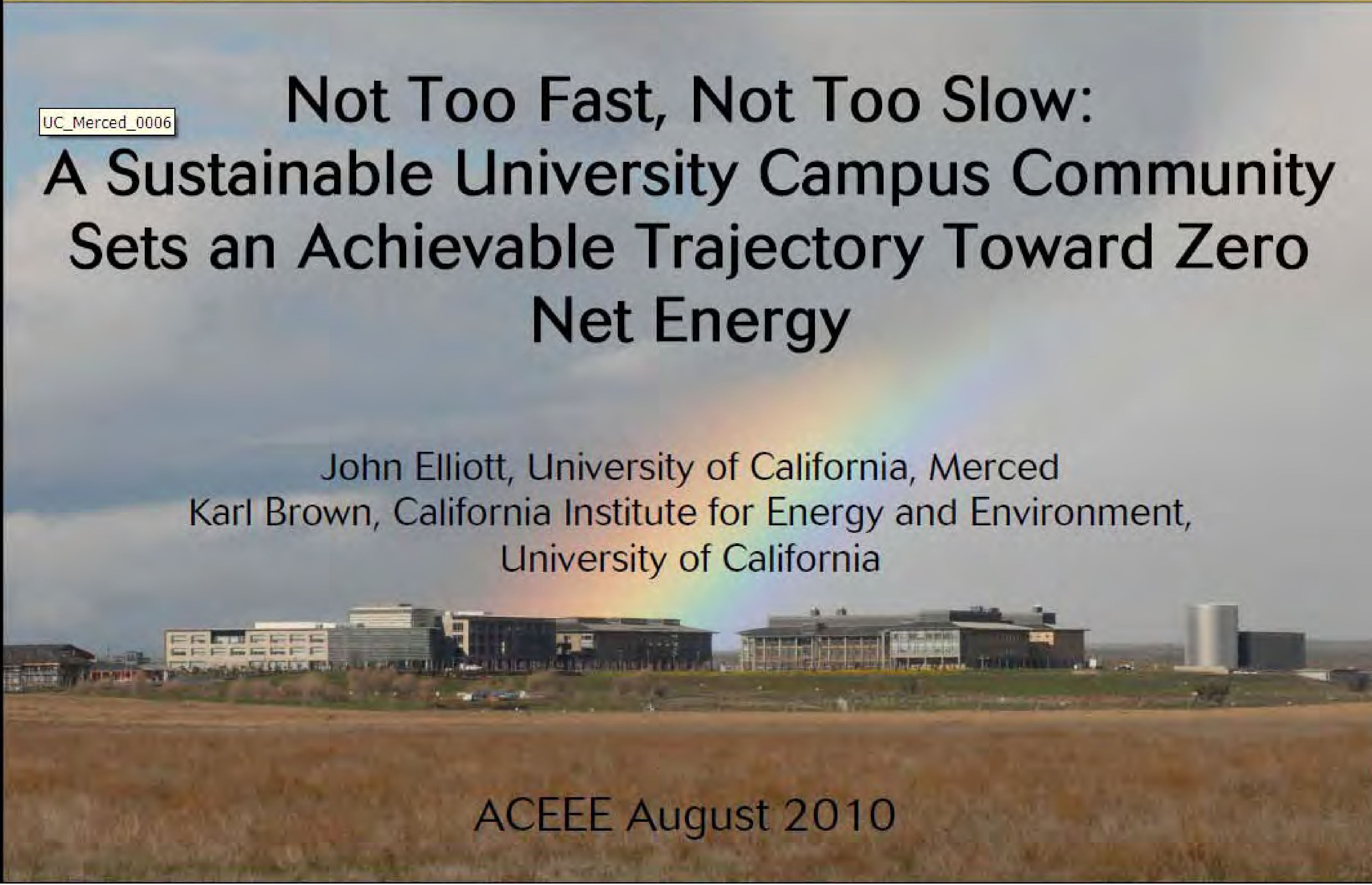
* *APPLIED MATHEMATICS AT THE U.S. DEPARTMENT OF ENERGY: Past, Present and a View to the Future* David L. Brown, John Bell, Donald Estep, William Gropp, Bruce Hendrickson, Sallie Keller-McNulty, David Keyes, J. Tinsley Oden and Linda Petzold, DOE Report, LLNL-TR-401536, May 2008.

UNIVERSITY OF CALIFORNIA, MERCED



Not Too Fast, Not Too Slow: A Sustainable University Campus Community Sets an Achievable Trajectory Toward Zero Net Energy

John Elliott, University of California, Merced
Karl Brown, California Institute for Energy and Environment, University of California

ACEEE August 2010

This is a story about UC Merced

Summary

Project outline

Model-based design for building cooling system

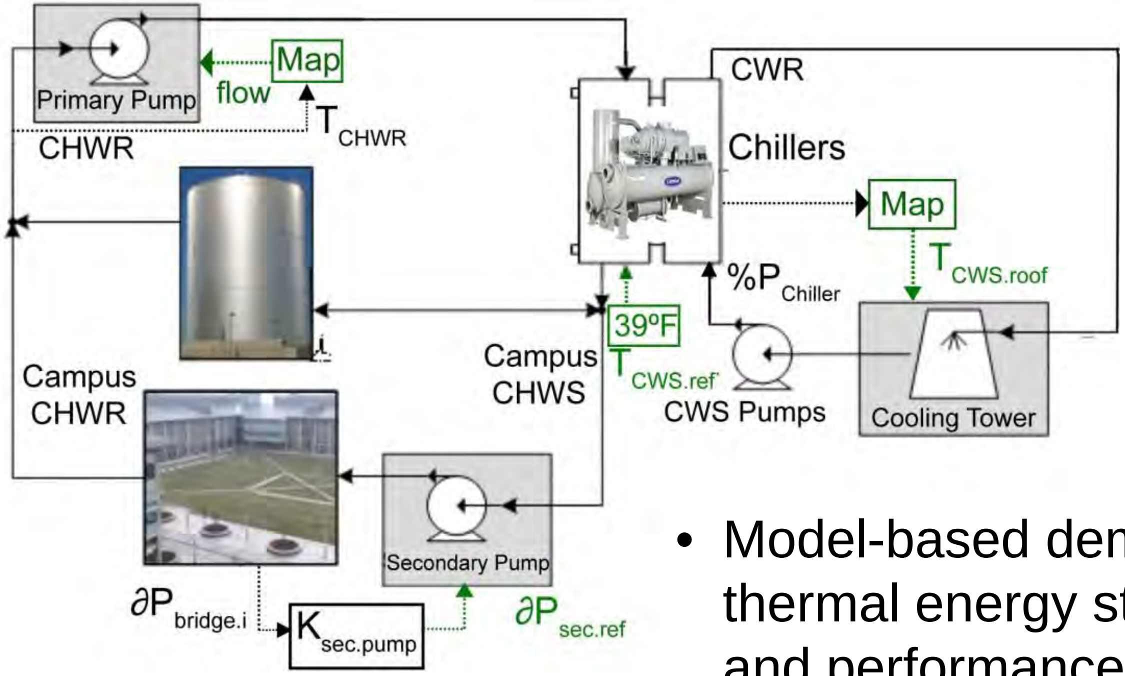
- Models: steady-state, high fidelity, reduced order-model for chilled water generation, storage, distribution and consumption
- Calibration: historical data based parameter estimation
- Optimization: receding horizon setpoint generation based on simplified models using weather forecast

MPC experiments and performance estimation

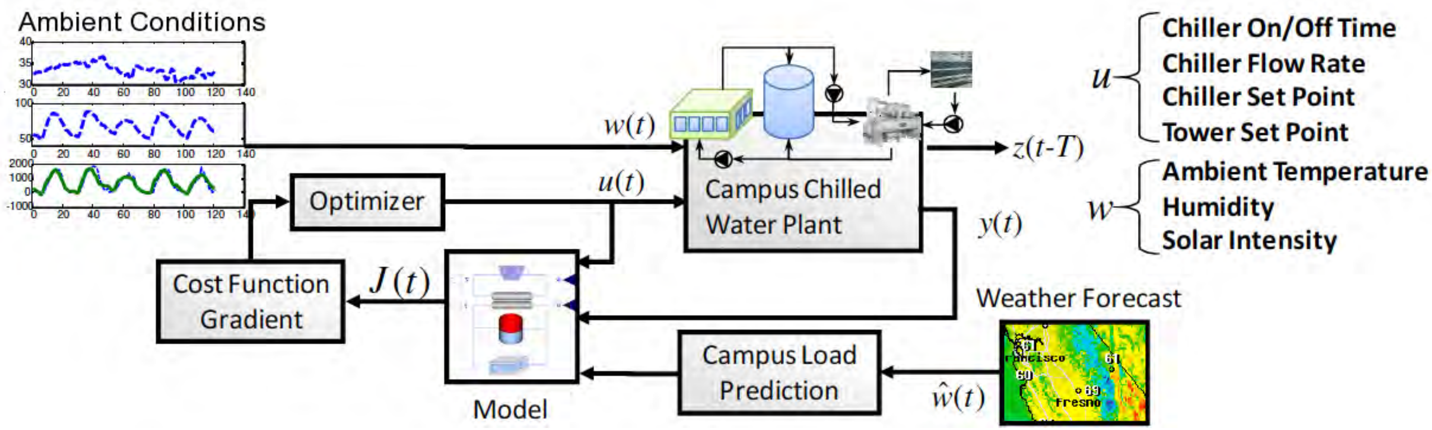
- Execution: operator-in-the-loop plant control
- Model re-validation: comparison between simulation and raw data
- Coefficient of performance definition and estimation

Practical limitations in achieving model-based predicted potential savings

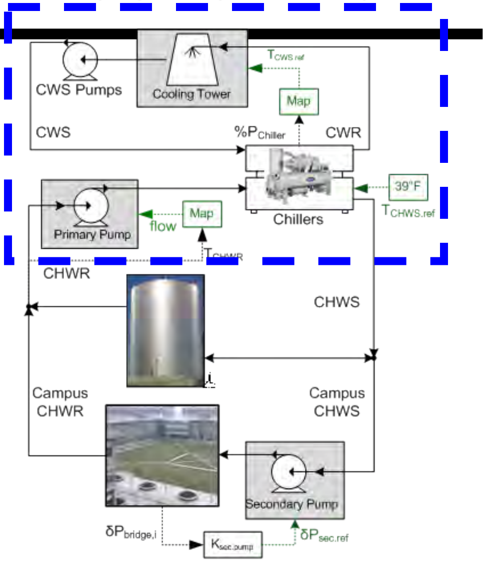
Model Predictive Control of Chilled Water Plant System



- Model-based demand forecasting for dynamic thermal energy storage and plant operation and performance optimization



Model Development – Static Models for Most of Plant



- **Quasi-Steady-State Models:** Transients of chiller, pumps, and cooling tower much faster than dominant system dynamics

- **DOE-2 Chiller Model:** biquadratic functions relate capacity and COP to evaporator and condenser temperatures

  - **Pump Models:** quadratic function relates pressure differential to flow-rate

  - **Cooling Tower Model:** polynomial function relates approach temperature to wet bulb temperature, leaving and entering water temperature, flow rate, and fan power

P_{CWP}: chilled water plant power

PLR: part load ratio

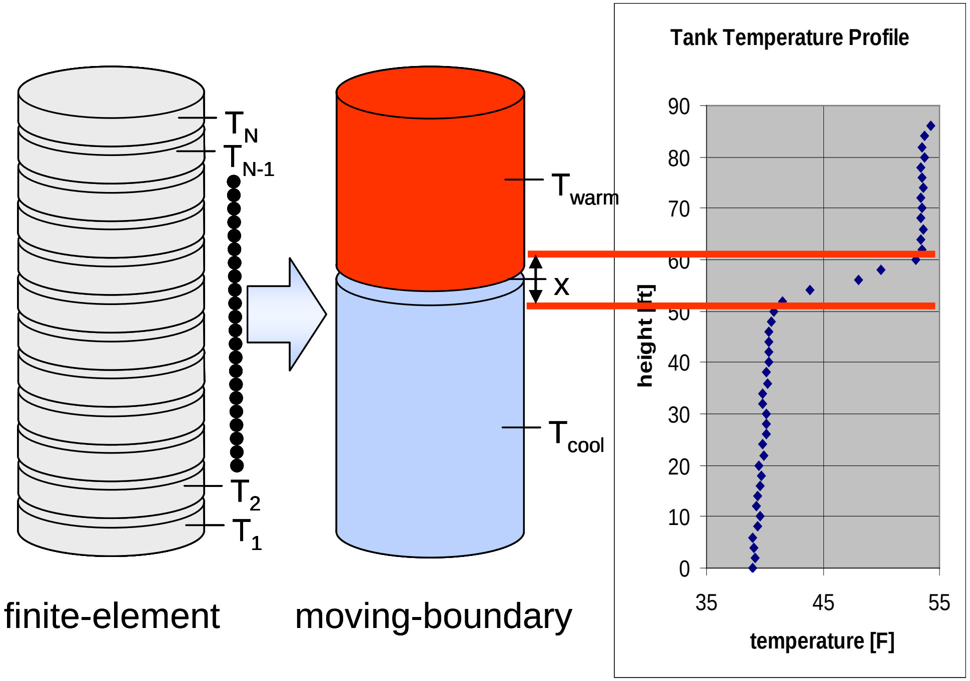
$$P_{CWP} = f(\underbrace{PLR, T_{CHWS}, T_{CWS}}_{\text{Set-Points}}, \underbrace{T_{wb}, T_{CHWR}}_{\text{disturbances}})$$

$$\dot{m}_{CH} = \frac{PLR \cdot Q_{avail}(T_{CHWS}, T_{CWS})}{C_p(T_{CHWR} - T_{CHWS})}$$

$$\left.\begin{array}{l} 5 \le T_{CWS} - T_{wb} \le 15,\ \ 0 \le PLR \le 1, \\ 10 < T_{CHWR} - T_{CHWS} \le 15,\ 0 \le \dot{m}_{CH} \le 235 \end{array}\right\}\ \text{constraints}$$

Dynamic Model Development – Chilled Water Storage Tank Model & Calibration & Validation

- Developed reduced order stratified tank model to reduce optimization time
- Accounts for heat transfer from ambient and across thermocline

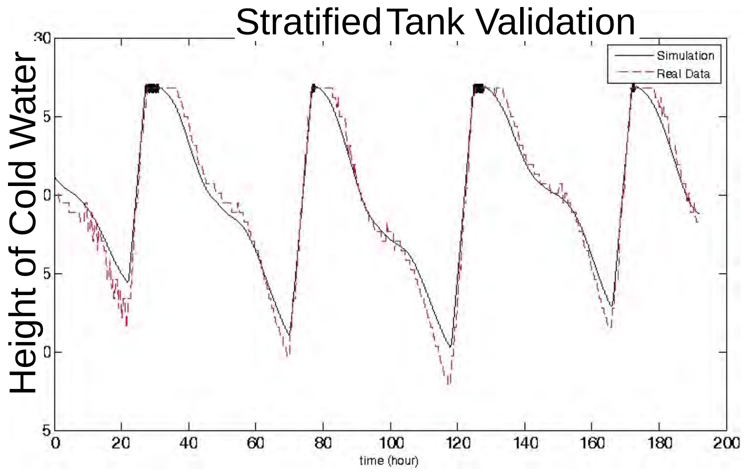


$x = m_1/m_{tank}$: mass fraction of cool water
$U_1 = x m_{tank} C_p T_1$: cool water internal energy
$U_2 = (1-x) m_{tank} C_p T_2$: warm water internal energy

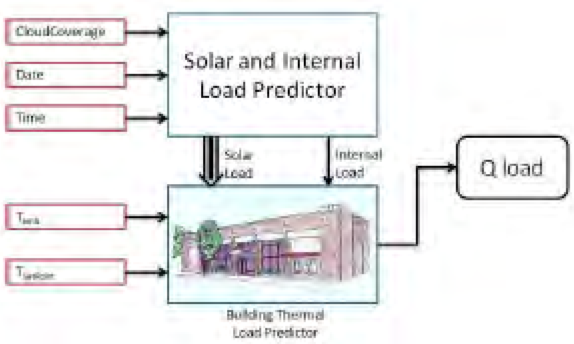
$$\dot{U}_1 = \dot{m}_{CH} C_p T_{CHWS} - \dot{m}_{campus} C_p T_1 + x k_1 (T_1 - T_{db}) + k_2 (T_2 - T_1)$$

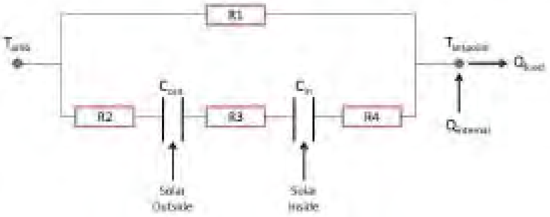
$$\dot{U}_2 = \dot{m}_{campus} C_p T_{CR} - \dot{m}_{CH} C_p T_2 + (1-x) k_1 (T_2 - T_{db}) - k_2 (T_2 - T_1)$$

$$\dot{x} = (\dot{m}_{CH} - \dot{m}_{campus}) / m_{tank}$$



Dynamic Model Development – Chilled Water Consumption I
Campus Load Model & Calibration & Validation





$$\dot{Q}_{Load} = \max(0, \dot{Q}_{internal} + \frac{T_{in} - T_{air}}{R_4} + \frac{T_{amb} - T_{sp}}{R_1}) \tag{8}$$

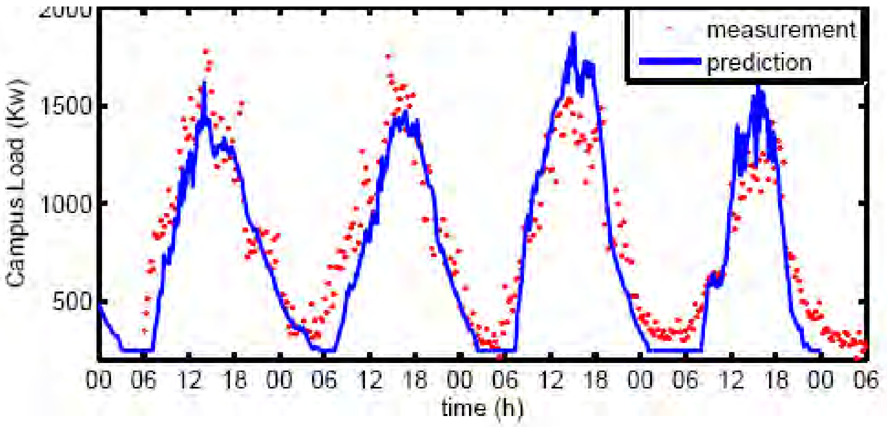
$$\dot{T}_{in} = \frac{\dot{Q}_{Solar,in} + \frac{T_{out} - T_{in}}{R_3} + \frac{T_{sp} - T_{in}}{R_4}}{C_{in}} \tag{9}$$

$$\dot{T}_{out} = \frac{\dot{Q}_{Solar,out} + \frac{T_{amb} - T_{out}}{R_2} + \frac{T_{in} - T_{out}}{R_3}}{C_{out}} \tag{10}$$

Campus load mode tuning parameters (can be made season-dependent)

Optimized Parameter	Description
t_{start}	starting time of the internal load
t_{end}	ending time of the internal load
$\dot{Q}_{Saturday}$	internal load for Saturdays
$\dot{Q}_{Sunday}$	internal load for Sundays
$\dot{Q}_{Weekday}$	internal load for Weekdays
θ_{in}	inside solar gain related to building geometry
θ_{out}	outside solar gain related to building geometry
R_1–R_4	resistors in Building Thermal Load component
C_{out}, C_{in}	capacitors in Building Thermal Load component

Model validation (measurements vs. model-based predictions)



MPC Design I

- **Purpose:** optimize efficiency by coordinating chilled water generation, storage, and consumption
- Hybrid model
  - State and input dependent switched system
  - Inputs are plant setpoint: chilled water tank charge level, chiller set-point, and cooling tower
- Optimization
  - Fixed tank operation mode profile (selected based on operator schedule)
  - Moving chiller operation mode window
  - Periodic terminal cost to approximate cost to go
  - Optimization cost: electric bill or coefficient of performance
  - Optimization variables: three setpoints and chiller start time

$$z_1(t) = \int_t^{t+T} C(\tau)P(x(\tau),u(\tau),w(\tau))d\tau$$

$$P(t) = P_{CWP}(t) + P_{campus}(t)$$

$$z_2 = COP = \frac{E^{Thermal}_{Generated}}{E^{Electrical}_{Plant}}$$

$$\boxed{\min_{\substack{u\in U \\ x\in X}} z(t)}$$

Subject to:

$$x(t+1) = f(x(t),u(t),\Phi(t),t)$$

$$y(t) = g(x(t),u(t),\Phi(t),t);$$

$$f = \begin{cases} f_1(x(t),u(t),\Phi(t),t); & \text{if } \dot{m}_{CHWS} \leq \dot{m}_{cmp} \\ f_2(x(t),u(t),\Phi(t),t); & \text{if } \dot{m}_{CHWS} > \dot{m}_{cmp} \end{cases}$$

$$u(t) = [T_{CWS,ref}; \dot{m}_{CHWS}; T_{CHWS,ref}] \in \mathbb{U}$$

$$x(t) = [U_a; U_b; z_a; z_b; T_{in}; T_{out}]$$

$$y(t) = [T_{CHWR}; z_b] \in \mathbb{Y}.$$

1) $T_{CWS,ref} \in [288, 295]K.$

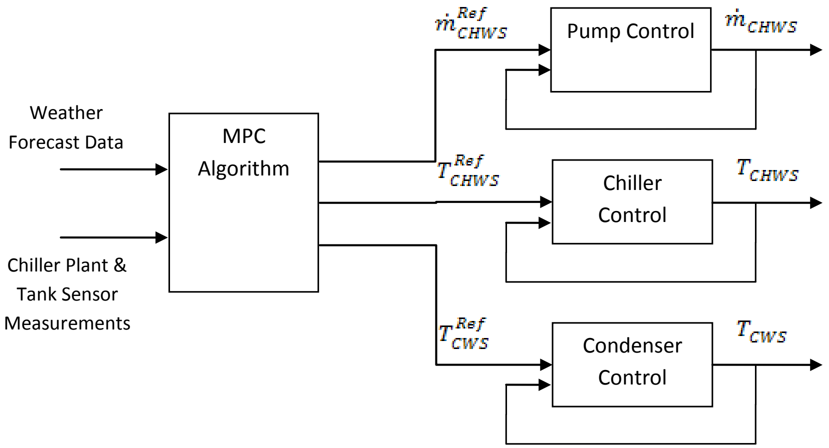
2) $\dot{m}_{CHWS,ref} \in \{0\} \bigcup [148, 235]kg/s.$

3) $T_{CHWS,ref} \in [276.5, 280.4]K.$

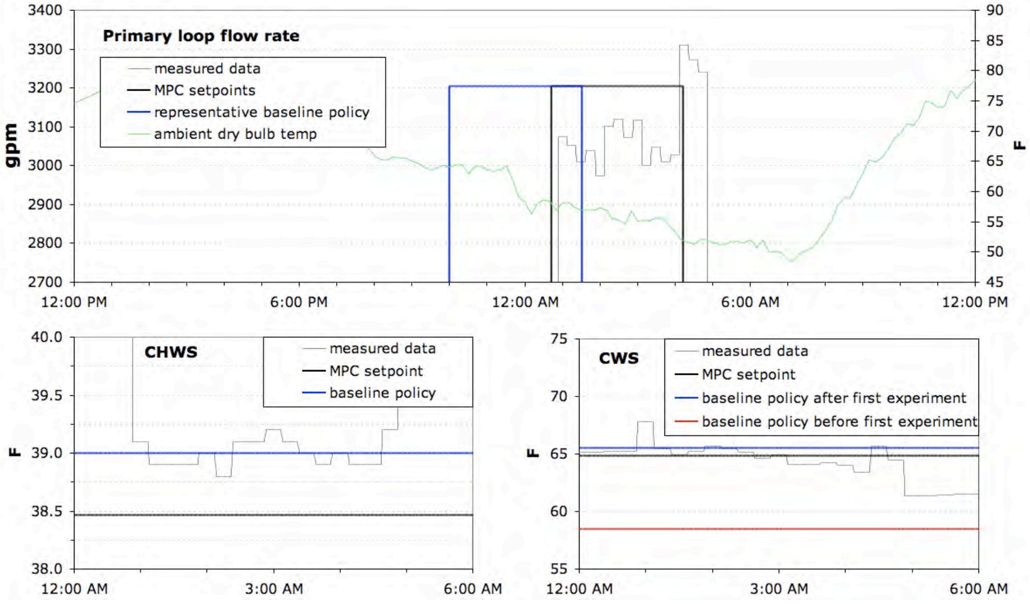
4) $T_{CHWR} \in [283, 295]K.$

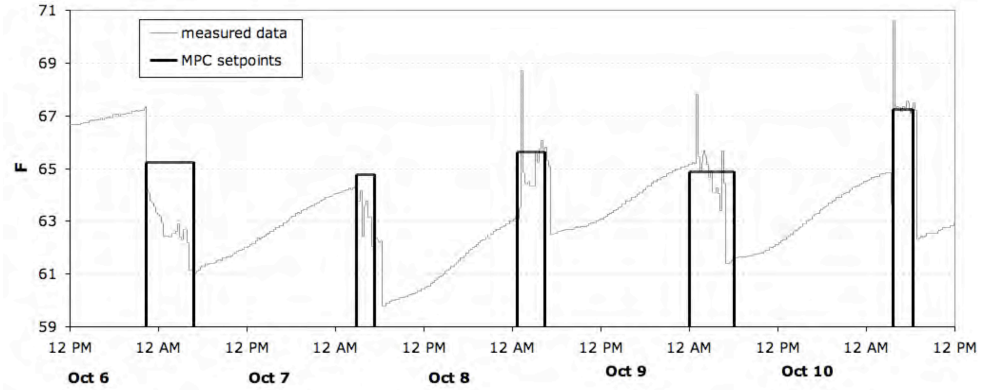
5) $z_b \in [0.3, 1]z_{tank}.$

Model Predictive Control of Chilled Water Plant System



Fall 2009 Experiment





Condenser water temperature set-points and TES charging windows

- 3-5% improvement in system COP
- Nearly 2% additional benefit from raising CWS

Data Analysis – Exp I Limitations to Potential Savings

- Factors for optimally loading of chillers
  - Limitations on (T_{CHWR}-T_{CHWS})
    - Tank and weather affects return temperature (T_{CHWR})
    - Baseline supply temperature (T_{CHWS}) near lower bound
  - Chiller pump flow-rate limited
  - MPC did not fully leverage pump flow-rate
  - Assumed 2 chiller configuration
- Leaving cooling tower set-point
  - Conservative limit on chiller lift to avoid surging
  - PIDs for set-point tracking needed tuning
- Lower tank capacity
  - Difficult to discern savings

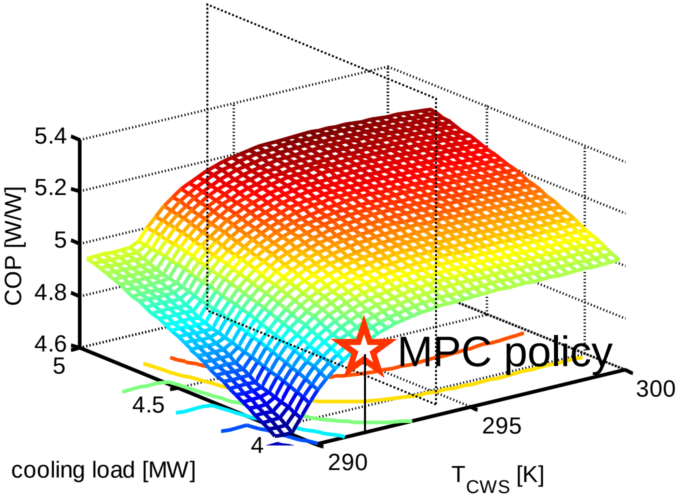


Fig: Chilled Water Plant (2 Chillers)

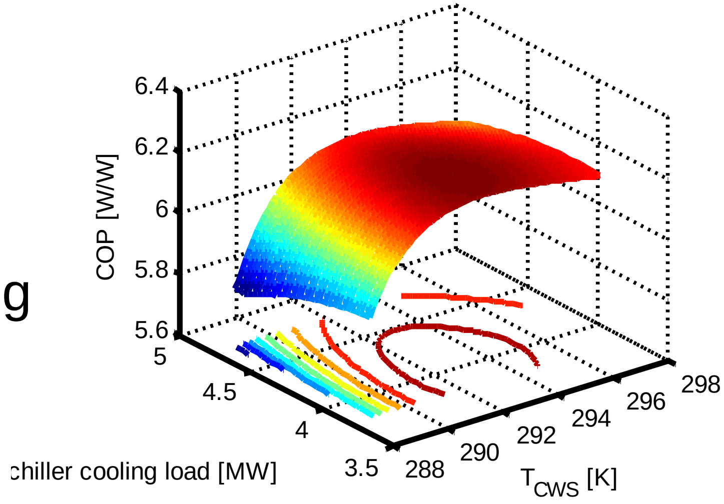


Fig: Chilled Water Plant (1 Chiller)

Key Points & Next Steps

- Energy and buildings. Importance of sector as building energy efficiency can be realized quickly.

- Current state of building controls. Design & implementation approaches using networked controls, standard control sequences and graphical entry.

- Energy efficient (high performance) buildings. **Achieving >50% over current standards (ASHRAE 90.1) is possible;** proof points occur for all sizes and climates; buildings designed using climate responsive design principles and building controls that integrate diverse components and recognize dynamics.

- Gaps in control performance. **Delivery process handoffs are a problem** and are where there is a loss of potential for energy savings in design, construction and operation.
  - Modeling – need frameworks that enable rapid construction & calibration (Modelica…),
  - Need to address uncertainty and coordination (supervisory control design)
  - Design flow automation (tool chain integration)
  - V&V (requirements formalization)
  - Address diagnostics more formally

- Case study: Merced campus control. Recognition of key dynamics, role of modeling and control, presentation of control results to campus operators.
  - Need to capture dynamics (storage and loads), uncertainty (weather), couplings (temporal);
  - Role and fidelity of modeling needed (ability to determine optimal set points for flow rates, temperatures);
  - Actionable information for fault handling (insufficient flow preventing higher COP)