A Systems Approach to High Performance Buildings
Issues, Scientific Challenges and Recommendations for R&D

ARTIST
Embedded Systems: Industrial Applications
Rome, Italy

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November 12, 2008
Key Points

- Market pressures on increasing performance for buildings
  - *Energy efficiency*: need to go to Net Zero Energy;
  - *Security*: need to improve false-alarm rates dramatically.

- Current best practices for high-performance buildings
  - *Functional integration* for increased efficiency.

- Barriers for dramatically improved high-performance buildings
  - Complexity, heterogeneity and emergent behavior of *networked systems*.

R&D needs in Systems Technology:

1. Design processes that address complexity explicitly;
2. Modeling and analysis that is focused on dynamics;
3. Explicit representation and management of uncertainty;
4. Design methodologies for networked embedded systems;
5. Supply and demand side energy demonstrations.
Building Systems
Aerospace Systems
Power Systems

UTC Power

Pratt & Whitney

Carrier

Otis

UTC Fire & Security

Hamilton Sundstrand
Energy, Comfort, Security Needs in Buildings are Evolving
UTC presence in buildings creates opportunities and research challenges

Carbon-neutral buildings by 2030
Buildings must be 4X-5X more energy efficient

Customer-focused solutions
Enabled by integrated systems

Threats becoming more complex
98% false alarms
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

Sources: Ryan and Nicholls 2004, USGBC, USDOE 2004
Systems of Systems Approach to Energy Efficiency
Creating and Exploiting the Interfaces between Sub-systems

Integration: The Whole is Greater than the Sum of the Parts
Problems: Heterogeneity, Complexity, Coordination...
FULL FACILITY INTEGRATION

1. Reduce energy demand early in design
2. Select systems to meet demand and optimize

- 25% primary energy footprint reduction at less than 7% incremental cost
- Payback 4.2 years total / 2.5 years new items

Optimized natural lighting
- Minimize heat gain (shading)
- Exploit natural ventilation

Energy Recovery Ventilation
- Optimally sized cooling systems

UTC Proprietary
BUILDING INTEGRATION

Marriott Hotel Building

- Manage heat gain
- Optimize control schedule
- Re-size air side equipment

UTC Proprietary
High-Performance Buildings: External Efforts

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

Among the low-energy design features used in this building are ground-source heat pumps, an under-floor air distribution system, heat recovery ventilators, an 18.2-kW PV system, daylighting, motion sensors, additional wall and roof insulation, and high-performance windows.

Zion Visitor Center

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

The building design incorporates energy-efficient features such as daylighting, natural ventilation, cool towers, passive solar heating, solar load control with engineered overhangs, computerized building controls, and an uninterruptible power supply (UPS) system integrated with the 7.2-kW PV system.

General Observations
Integrated design of building systems can provide substantial efficiency gains.
Actual energy performance lower than predictions.

Failure Modes Arising from Detrimental Sub-system Interactions

- Changes made to envelope to improve structural integrity diminished integrity of thermal envelope (e.g. “retainer wall acting as a fin”)
- Adverse system effects due to coupling of modified sub-systems:
  - changes in orientation and increase in amount of glass on façade (affects solar heat gain)
  - indoor spaces relocated relative to cooling plant (affects distribution system energy) while simultaneously reducing plant size
  - improper thermal bridging of window frames and adjoining walls resulted in heat loss, adversely impacting heating energy
  - Trombe walls for passive heating add to cooling loads in summer requiring façade design (e.g. overhang) to provide shade
- Lack of visibility of equipment status/operation and large uncertainty in loads (e.g. plug, occupancy, leaks), leading to excess energy use

Building Systems Integration Challenge

Complex* interconnections among building components

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


Basic Science To Enable Energy Savings

Requirements & Architecture Exploration: BIM and Tool Chains for Integrated Mechanical and Control Design

Integrated Design: Decentralized Control Design & Analysis for Robust Operation

Implementation: IT enabling continuous commissioning and occupancy and plug load estimation for detailed energy management

Needs for Basic Science and Measurement for High Performance Buildings

Architecture & Envelope Optimization: Whole building simulation, uncertainty analysis, and definition of abstraction layers

Mechanical Systems Specifications & Supervisory Control: Multi-scale (zone-room) modeling, computation and hybrid system optimization

Rapid and Robust Implementation: Network design and data assimilation
Energy Savings in Commercial Buildings

- **Information Systems & Networks**
  - Occupancy, utility rate, weather…

- **Comfort & Ventilation Systems**
  - Ventilation, air movement…

- **Thermal Systems**
  - Thermal recovery, storage…

- **Green Buildings**
  - Architecture, envelope…

Energy Efficiency Gains:
- Baseline Footprint (ASHRAE 90.1)
  - 20-30% ↓

  - 10-15% ↓

  - 10-15% ↓

  - 5-20% ↓

45-80% Demand Reduction

Technology Risk & Readiness

- Reduce risk/enhance maturity
- Make solutions scalable & robust
- Drive commercial adoption
DOE Seed Projects Kicked Off: Oct. 2008
Technology Maturation and Demonstration at University of California - Merced

- Integrated Cooling & Thermal Storage
  Approx. 20% total building energy
- Integrated Security & HVAC Systems
  Approx. 20% HVAC system energy
- Real-time Visualization of Model-based Energy Performance
- Model Predictive Control of HVAC systems
- Integrated Energy Information Systems
  Approx. 20% total building energy
- Occupancy-based energy management
European Movement on Energy Efficiency

Established practice: a 2nd example

Climate control in the atrium of the office building Grafenau in Zug, Switzerland

Input to building automation system:
- Outside temperature
- Atrium temperatures
- Solar radiation
- Wind and rain
- Time
- User commands

Control actions:
- Blinds
- Vents

Use of Weather and Occupancy Forecasts for Optimal Building Climate Control (OptiControl)

- ETH Zurich, Terrestrial Systems Ecology (Project lead)
- ETH Zurich, Automatic Control Laboratory
- EMPA Building Technologies (ETH domain)
- MeteoSwiss, Federal Office of Meteorology & Climatology
- Siemens Building Technologies

EU BAC CERTIFICATION

• REQUIREMENTS:
  - PRODUCT:
    - Compliance test vs EN15500
    - Compliance test with eu.bac certification specific tests
  - MANUFACTURING PROCESS:
    - Existence Quality Management System and Quality Plan
    - Inspection of manufacturing site
Proposed R&D Investments and Program Tracks

**Track 1:** Design, delivery and operations
- BIM (data repository)
- Concurrent design methods (GBXML, IBECS)

**Track 2:** Systems and Technologies
- UFAD
- Active Facades
- Concurrent design methods (GBXML, IBECS)

**Track 3:** Science, Methods, and Tools
- SPARK
- EnergyPlus
- CFD
- New design paradigms: Integrated multi-domain models analyzed in multiple levels (topology ↔ mechanical/electrical systems ↔ multi-scale controls ↔ sensors and networks ↔ BMS)

**Near-term Projects**
- BIM (data repository)
- Concurrent design methods (GBXML, IBECS)

**Mid-term Projects**
- Functional decomposition and synthesis of beneficial interfaces
- Integrated façade/heating/cooling/ventilation/lighting/power systems & controls

**Long-term Projects**
- Energy/Exergy flow fundamentals and visualization tools
- ROM for building thermals and airflows (thermal comfort, IAQ)
- Computational Science and Engineering Methods for Whole Building Systems
- Tools for control and estimation of multi-scale dynamics (passive HVAC systems…)
- Whole building system optimization and uncertainty analysis techniques
- Diagnostics and commissioning techniques (data assimilation…)

**Maturation of Methods, Tools & Technologies**
Strategic Research and Development Plan

SEEDLINGS
$0.5 M PROJECTS

FOCUSED RESEARCH PROJECTS
$5 M PROJECTS

LARGE-SCALE TECHNOLOGY DEMONSTRATIONS
$5 - $50 M PROJECTS

NOW 6 MO.

PHASE I 1 YEAR

PHASE II 1 YEAR

PHASE III 2 YEARS

2018

Virtual Scale-Up

1. Monitoring, Prognostics & Commissioning
2. Building Operating Platform
3. Integrated Design Methodology & Tools

Concept Feasibility

Sub-Scale Facility

Medium-Scale National Research Facility

Full-Scale Demonstration
1. Zero Net Energy Building
2. 50% Efficient Retrofit Building

Concurrent Projects

1. Data assimilation & fault diagnostics
2. Dynamic comfort modeling & optimization
3. Model predictive control
4. Design flows for networks & controls
5. Energy modeling infrastructure
6. ....
7. ....
8. ....

Workshops

Virtual Prototyping

CONCEPT FEASIBILITY

VIRTUAL PROTOTYPING

TRL4

TRL6

TRL9
Backup
HiPerBRIC Vision

Enable transformation of U.S. Commercial buildings sector in 20 years, starting NOW

– Save >4 Quads of energy and reduce >400 million tons of CO₂ annually
  • Reduction in energy consumption: 90% in new buildings; >50% in retrofits
– Enhance health, comfort, safety/security and water usage while gaining energy efficiency
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National Laboratory-Industry-Academia Partnership

INDUSTRIES

United Technologies
UTC

Market Knowledge
Commercialization Paths
Product Oriented R&D

Unique value:
focus on systems

Prof. Matthew Tirrell
Dean, College of Engineering
UC Santa Barbara

Prof. Igor Mezić
Department of Mechanical Engineering
Institute for Energy Efficiency

INDUSTRIES

NATIONAL LABS

Dr. Michael J. McQuade
Sr. VP, Science & Technology

Dr. David Parekh
Director, UTRC
UTC

Precompetitive Basic & Applied R&D
Tech. Support for Codes, Standards & Policy
National Experimental Facility
Neutral Venue for Market Competitors

Dr. Steven Chu
Director

Dr. Arun Majumdar
EETD
LBNL

ACADEMIA

Basic Research
Education & Training
Neutral Venue for Market Competitors

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UC Santa Barbara
Integration-Enabled High Performance Buildings
Robust engineering and operation of complex interfaces

Integrated Façade, lighting and HVAC

Concept: Utilize building façade to balance artificial and natural lighting, match lighting loads with occupancy and HVAC demand

Challenge: Fundamental understanding of lighting, building material properties, and their dynamics relative to indoor/outdoor disturbances (e.g. weather, lighting, occupancy…), co-design of building façade, lighting and HVAC systems, robust control architectures, uncertainty

Benefit: >50% reduction in lighting demand while matching HVAC demand
Integration-Enabled High Performance Buildings
Robust engineering and operation of complex interfaces

Integrated Envelope and HVAC Systems
Natural, Passive and Hybrid Ventilation

Concept: Hybrid HVAC systems to take advantage of building material for thermal storage, natural ventilation and passive heating/cooling systems to match occupancy demand

Challenge: Fundamental understanding of energy/thermal/air flows and their coupling to dynamics of disturbances such as weather, occupancy, co-design of building HVAC and envelope systems, robust control architectures, uncertainty

Benefit: 30-50% reduction in ventilation energy demand, gains in occupant health/productivity

Designing UFAD Systems: Updated Guidelines August 8, 2006 (F. Bauman, CBE, McCoy UFAD Workshop)