Gopstein, Avi (S4)

From: Hopkins, Asa (S4)
Sent: Thursday, August 25, 2011 10:04 AM
To: Gopstein, Avi (S4)
Subject: FW: Update: DOE Quadrennial Technology Review (DOE-QTR) Building and Industrial Efficiency Workshop May 17th, Pittsburg, PA
Attachments: NSF CMMI Workshop Report v_4.0.pdf; Complete_book_NSF_CMMI_Workshop.pdf

---

From: Alleyne, Andrew G [mailto:alleyne@illinois.edu]
Sent: Monday, May 23, 2011 8:19 AM
To: Steven E. Koonin, Under Secretary for Science; Hopkins, Asa (S4); Chambers, Megan (S4); Lin, Cynthia (S4); Alexander, Kathleen (S4)
Cc: Koonin, Steven
Subject: RE: Update: DOE Quadrennial Technology Review (DOE-QTR) Building and Industrial Efficiency Workshop May 17th, Pittsburg, PA

Dear Steve, Kathleen, Asa, Megan and Cynthia

Many thanks for the invite to participate in the QTR workshop last week. I enjoyed it and learned some new things.

As I'd mentioned to some of the participants, we held an NSF-sponsored workshop last year on a similar theme focusing on the Buildings aspect of it. In particular, we examined the modeling/dynamics/controls aspects since this was the community that was holding the workshop.

To fill you in on what we came up with, I am attaching a copy of the final report as well as the presentation book from the workshop. Feel free to use the information in here as you come up with your own QTR. I'd be happy to provide more detail on what the participants came up with if you feel that is needed for anything. Note: the final report was written before the Building Hub was announced so it's possible that with the Building Hub the called for "co-laboratory" aspect has already been created within the past year.

Please let me know if I can be of further assistance.

Best,
Andrew

Andrew Alleyne
Ralph & Catherine Fisher Professor of Engr.
Associate Dean for Research
College of Engr. University of Illinois
MC-244
1206 West Green Street
Urbana, IL 61801
217-244-6448 (phone)
217-244-6534 (fax)
alleyne@illinois.edu (e-mail)

Assistant: Lori Melchi
Office of Associate Dean for Research
310 Engineering Hall, MC-266
1308 West Green Street
Urbana, IL 61801
Phone: 217-244-6449
Fax: 217-333-7852
e-mail: lmelchi@illinois.edu

NSF CMMI Workshop on Building Systems

Table of Contents

	Page #
1. EXECUTIVE SUMMARY	2
2. INTRODUCTION AND MOTIVATION	3
3. CROSS CUTTING THEMES	6
4. AREA THEMES	8
A) MODELING	8
B) ESTIMATION/DIAGNOSTICS	10
C) COMMUNICATION	11
D) CONTROL/OPTIMIZATION	13
5. DISCUSSION	16
6. CONCLUSIONS AND RECOMMENDATIONS	17
7. ACKNOWLEDGEMENTS	18
8. REFERENCES	18

1. EXECUTIVE SUMMARY

Motivation and Purpose

Buildings have a huge environmental and societal impact that is growing with increasing worldwide urbanization. To address this economically and environmentally important area the National Science Foundation (NSF) sponsored a Workshop on Building Systems at the University of Illinois Urbana-Champaign on 24-25 May 2010. The purpose of this workshop was (1) to assist NSF with identifying priority areas for potential funding for improved energy efficiency of buildings and for the comfort, safety, and productivity of their occupants, and (2) to raise awareness in the controls community of the research issues in this area. The participants were from industry, government, and academia.

Fundamental Issues

The workshop participants discussed the broad areas of (i) modeling, (ii) sensing and estimation, (iii) communication, and (iv) controls/optimization to determine the fundamental issues in these areas they relate to building controls. Key issues identified from each area were:

Modeling issues: (a) Existing analytical models do not adequately predict the real behavior across the relevant range of dynamics; (b) current numerical software is difficult for users to use; and (c) models created from integrating models of components, either analytical or numerical, are not easily simplified for control algorithm development, decision making, etc.
Estimation/Diagnostics issues: (a) Estimation and diagnostics are essential to retrofit of existing buildings; (b) sensor networks in large buildings are extremely complex from which it is easy to get data, but hard to obtain useful knowledge for diagnostics/estimation; (c) systems and sensors change over time; (d) robustness to humans in the loop is essential.
Communication issues: (a) Building network configuration and maintenance is a labor intensive endeavor; (b)design, specification and deployment of sensor networks are ad hoc, typically optimistic in cost and performance, and with no ability to reliably evaluate cost-performance trade-off in the early stage of the design; (c) understanding of human-machine interfaces to ensure persistent energy efficient building system operation is lacking; (d) integration and interoperability of building information sources (e.g. sensors, building usage schedule, weather data, power distribution, power generation and delivery, security, etc.) is insufficient; and (e) powering distributed sensors and communication networks may be challenging from an energy viewpoint.
Controls and Optimization issues: Control technologies and optimization strategies are needed (a) for building retrofit; (b) for minimizing the number of required sensors and for robustness to sensor location/variability/faults; (c) for rapid technology deployment/adoption; and (d) for integration of buildings with the electricity grid. Additionally, (e) systems must account for human factors and psychology in their operation.

The body of this report discusses each of these issues in these areas greater detail.

Crosscutting Themes

In addition to fundamental areas, the participants sought to identify crosscutting themes within the technical sub areas. Several such themes emerged from the workshop. Foremost was the importance of prioritizing issues related to retrofitting existing commercial, industrial, and

residential buildings, since the vast majority of buildings that will be in existence in 2030 are already 10 years old. Other recurring themes were (1) the importance and dearth of suitable modeling frameworks and tools, (2) the importance of accounting for psychology, human factors and human-machine interaction, (3) complexity and emergent behavior of building systems, and (4) the need for adaptation and learning to account for changing use and aging on time scales ranging from less than a day to several decades.

Recommendations

Given the societal impact and relevance of the various building systems in use today, as well as the fundamental intellectual challenges discussed and uncovered in this workshop, we strongly recommend that the National Science Foundation, in close collaboration with other agencies such as DoE and possibly NIST, take a leadership role in advancing the *science* of building systems within the context of critical translational research. Currently, the large scale systems science tools needed to address the building systems space, incorporating the building systems constraints (i.e. uncertainty, changing behavior, humans-in-the-loop, faults present, etc.), are not readily available in any of the technical areas discussed in the workshop. We advocate a core research program in building systems science with a funding model that supports the entire cycle of research and education.

Specifically, given the scope of the problem, we advocate a program similar in scope and structure to the George E. Brown, Jr. Network for Earthquake Engineering Simulation (www.nees.org). This would be a "collaboratory" distributed across the United States that would examine different aspects of the building systems science base but coordinate in a streamlined fashion.

Note: subsequent to the workshop, the DoE ERIC hub on buildings was awarded to a Pennsylvania consortium. The workshop sentiment is still for NSF to advocate and enable a broad national engagement on this topic. It will take many different perspectives to make progress.

2. INTRODUCTION AND MOTIVATION

Currently, buildings account for a large fraction of global energy usage. In the U.S. alone buildings consume 39% of total energy usage, including 71% of electricity and 54% of natural gas [1]. This is illustrated in Figure 1. Moreover, it is estimated that buildings contribute to 40 % of the worldwide greenhouse gas emissions [2]. For buildings, the energy consumption of 41 quads is on par with all transportation systems and the carbon footprint is actually

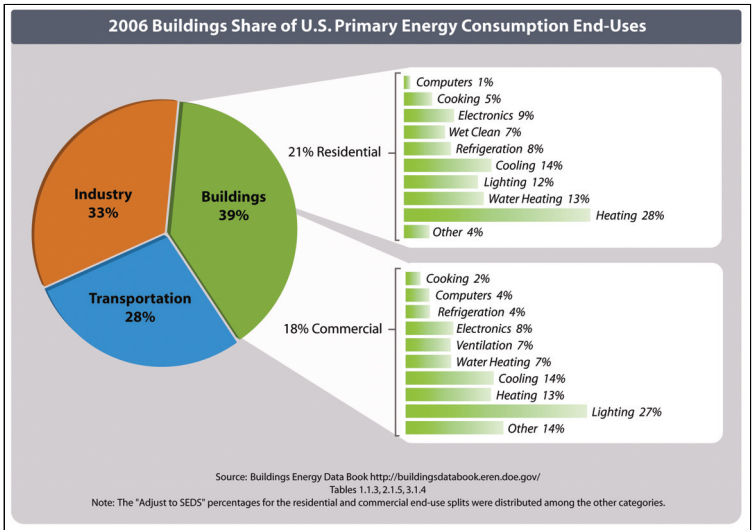


Fig 1. U.S. Energy consumption by sector

higher. Part of this environmental impact is due to the building design and part is due to the building operations over its lifecycle. As the world population becomes more and more urbanized, the environmental pressures will increase. Therefore, there is a large energy cost and a large environmental cost to be paid and this cost will rapidly increase with the current pace of global urbanization. Demand for building space will not decrease. Therefore, if nothing is done to increase the overall system efficiency, there will be a true economic and environmental threat appearing in the not too distant future. This building energy crisis has received remarkably little attention from the research community compared to the focus on new sources of energy or energy conservation within the transportation sector.

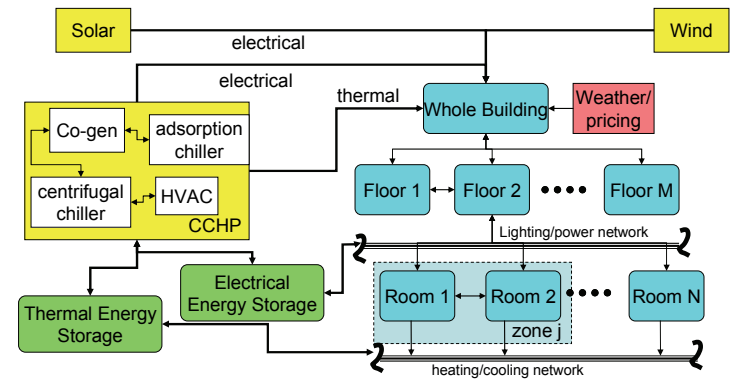


Fig. 2. Building schematic as a complex system

In a certain sense, modern commercial buildings can be thought of as extremely complex heterogeneous networks of dynamic systems. This is depicted schematically in Figure 2. In addition, these systems must interact with human users and be subjected to regulatory constraints. There are a multitude of available technologies that can be used to improve the performance of these systems including active facades, ventilation, chilled beams, window treatment, solid state lighting, and HVAC/R controls. The state of the art research in the general field of buildings and building technologies has allowed large improvements in the individual components. However, due to the fragmentation of the design and build approach to these systems, the interplay among the subsystems is often neglected. Moreover, the interaction of these subsystems with the building occupants is not well understood and challenging to predict. As an example of the interplay, there is interplay among all of the various heating and cooling energy exchange systems within the building including the HVAC components, air zones, and building structure. Additionally, lighting systems can be designed to take advantage of natural light but must compensate with internal solar load as a potential system disturbance on the HVAC. Lighting systems, which are the second largest draw of power in buildings, are also networked in the sense that adjacent lighting systems affect the number of lumens present in an enclosed space. All of these subsystems operate on one or more networks of information flow throughout the physical building. In addition, these networks can communicate with the outside world in terms of weather forecasting or energy price forecasting.

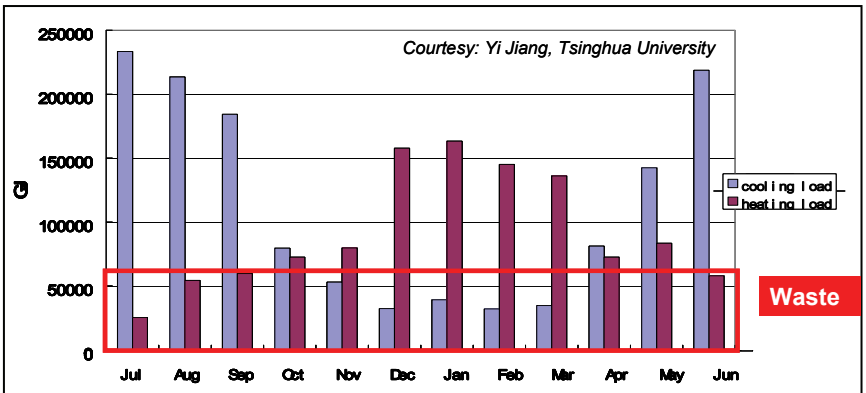


Fig. 3. Poor commissioning leading to wasted energy

Buildings are clearly high impact examples of complex "systems of systems" that will benefit from examining the physical aspects of building systems (e.g. lighting, power systems, heat transfer, fluid mechanics) in addition to the communication network and decision systems activity. One example of the interplay which illustrates the inefficiencies present in the system is the simultaneous overlapping usage of both heating and cooling within a building HVAC system. Figure 3 shows an unnamed U.S. university campus which simultaneously implements both heating and cooling systems throughout the year. Clearly we collectively can do better than the current practice.

2.1 NSF CMMI Workshop

Given the scope of the technological problem and the societal impact of the application area, it was deemed valuable to convene a focused group of scientists and engineers to study the issue from a broad array of perspectives. A workshop was proposed, supported by NSF, and held at the University of Illinois, Urbana-Champaign campus on May 24-25 2010. The workshop had over 3 dozen participants from industry, academia and government who participated in a series of presentations and detailed discussions. The primary goals for the workshop were twofold. First, we wished to raise awareness within the academic controls community as to the rich intellectual merit of the research needs present within the context of building systems. The controls community is one which has much to offer this societal problem but there is a lack of understanding of how it could engage. By bringing researchers from a wide variety of backgrounds, including over half from outside the general buildings arena, we targeted the dissemination of information regarding opportunities. The second goal was to identify key challenges and barriers as well as propose potential solution paths that could be taken by our research community; possibly in collaboration with other communities. These research challenges and opportunities were identified by over 6 hours of interactive discussions sessions following 5 hours of presentations.

2.2 Workshop Agenda

The workshop began with 8 presentations from a combination of industry, academia and government.

- Colin McCormick (Dept of Energy): "Building Systems: Measurement, Simulation and Control"
- Michael Wetter (Lawrence Berkeley National Laboratory): "Building Modeling and Simulation to Support Controls Design and Operation"
- John Beane (Honeywell Research): "Energy Related Building Systems Research"
- Prashant Mehta (UIUC): "Estimation and Control Problems in Buildings"
- Steven Bushby (NIST): "Building Automation Control Networks"
- Jim Braun (Purdue): "Embedded Intelligence to Enable Intelligent Building Systems"
- Luke Leung (Skidmore Owings & Merrill): "Burj Dubai Natural Environment and Building Control"
- Amit Chakraborty (Siemens Research Center): "Optimization for Building Systems Asset Allocation"

The goal of the presentations was to give a broad overview of the state-of-the-art from the perspective of multiple user communities. They posed problems and challenges that have not yet been met by the research community due to gaps in the systems and control knowledge base within the buildings science community. These presentations generated interest among the participants and fed directly into the working group discussions.

2.3 Working Groups

There were 2 separate working group sessions, one in the afternoon of the 1st day and one the morning of the 2nd day. The participants attended 2 separate sessions so as to get a mix of opinions and input on multiple topics. The working groups were aligned along the topics outlined earlier.

a) Modeling and Simulation
b) Estimation and Diagnostics
c) Communication
d) Optimization and Control

The working groups were asked to:

- Assess the state of the art
- Identify key barriers or challenges that could be opportunities for the controls community
- Outline potential research projects that could address these barriers

The working groups each had leaders and scribes to capture the input of the participants. The second morning, a specific integration session was held to combine and synthesize the input from co-leaders on each session. These were then put into presentation form and presented to the entire workshop community over a working lunch. This outbrief activity gave the opportunity for all participants to have additional input. Subsequently, the workshop advisory committee retreated to begin assembling the workshop report.

The rest of this report gives a summary of the workshop outcomes including descriptions of the discussions that took place within the four main thematic areas. Additionally, summaries of recommendations are also present along with conclusions suggesting next steps.

3. CROSS CUTTING THEMES

There were several themes that cut across all of the technical discussions throughout the workshop. In this section, we give an overview of these and illustrate how they are relevant to several different technical areas.

A primary message emerging from this workshop was the relative impact that could be had by developing translational research approaches to systems science specifically for buildings. In particular, the turnover of building stock is relatively slow with the vast majority of current buildings still likely to be in use in 2030 and beyond. The biggest impact that the systems and

controls community could have would therefore be in the retrofit space given this slow turnover. Existing buildings would be reconfigured with new information gathering systems (sensors), new communication capabilities, and new mechanical systems that could actuate the energy flow within the building space. From a systems science point of view, the retrofit problem is more challenging than the new construction problem since there is often incomplete information about the current nature of the physical plant and it is challenging to reconfigure the plant to achieve better dynamic performance. Solving this retrofit problem will translate to solutions readily available for new building design and construction.

Another theme that emerged throughout the workshop was the lack of *appropriate* models for estimation, diagnostics, decision and control. The simulation tools available today are not well suited for dynamic prediction because they were never designed for the purpose. The models that drive these simulation tools can also be more complex than necessary for the purpose of control. Moreover, these tools are ill suited for formally handling complex heterogeneous physical system representations that span multiple time scales. The appropriate simulation tools and model structures would enable estimation and diagnostic algorithms because they would give a model structure that could be used to determine what is nominal behavior and then deviations from this. The right modeling structure would then facilitate robust scalable decision-making architectures. The desired modeling structure includes the ability to capture the interaction of the building inhabitants with the envisioned cyber-physical surroundings which leads to the third cross-cutting theme.

While many of the participants entered the workshop focusing on the physical aspects of the building systems problem, a presentation early on by J. Beane from Honeywell brought home the point that the interactions with the inhabitants is critical and often overlooked. During the workshop the comparison was made with another complex dynamic system: a large jetliner. The jetliner has a ground-based maintenance crew that is dedicated to maintaining it in perfect working order prior to usage. The jetliner's behavior is ensured to be the same as the previous usage and common to all jetliners of the same class and make. Additionally, there is a highly trained flight crew that is responsible for operating the machine. The passenger inhabitants of the jetliner are able to make small changes to their individual environments but nothing major. This is completely different from a building as a large complex system. There is no trained crew to maintain the pristine operating condition. The inhabitants have a major say in the operation of the building even going as far as reconfiguring the layout of walls, windows and doors. Additionally, the inhabitants can provide disturbances that are large enough to affect the overall energy performance of the system. Anecdotes were shared about sensors being intentionally deactivated by building inhabitants or building management systems suspended 'temporarily' but never turned back to normal operation. The ability to understand the interactions of the complex collective of humans with the complex cyber-physical system and then utilize this knowledge to control the building system emerged as a key scientific challenge.

A fourth theme that emerged was the complexity of building systems, particularly for commercial buildings that occupy our increasingly urbanized cities. L. Leung of Skidmore Owings & Merrill gave two separate examples of very large scale building systems project in the Middle East and Far East. These were extreme cases but all the workshop participants agreed that any research performed or solutions proposed should be scalable such that it can be applied

to a small building system or large building system. Even residential systems should be considered in a scalable framework since it is envisioned that Smart Grid capabilities may turn neighborhoods into mini-grids or cooling/heating districts that need to coordinate amongst themselves. J. Stoustrup from Aalborg University illustrated examples of where that is already being done in Denmark but currently in a decentralized individual setting.

The fifth theme that cut across technical areas was the notion that, unlike the jetliner example, buildings *will* be operated in conditions that are not what they were designed or commissioned for. Therefore, any building systems activity will have to operate in the face of failures to parts of the system. In other words fault tolerance is mandatory. Any approach to addressing the complex building system problem must be robust to failures either by physical design, e.g. chiller redundancy, or by operating mode, e.g. distributed control. It may also be possible to identify faults and adapt the behavior of the system to accommodate this. Both the learning/adaptation and the robustness are part of the same need for consideration of operating under failed conditions for part of the system.

4. TECHNICAL THEMES

During the breakout sessions, each of the technical themes were discussed within the following context

a) **Description of the research area**
b) **Technical research challenges**
c) **Recommendations for advancing the field**

In the following report on the areas, this format will be followed. It was challenging to distill all the ideas that emerged but the breakout leaders and scribes were able to consolidate the input from over 3 dozen people into clear concise bulleted lists. However, the reader should note that the results presented in the next four sections are not given in a prioritized order. All challenges that remained in the report were deemed worthy and all recommendations were worth considering.

4A. MODELING AND SIMULATION

<u>Description of the area</u>

The energy systems in modern buildings, especially HVAC systems are modeled and simulated with significant details in large-scale, special-purpose software packages such as Energy+ and DOE-2 & Trnsys. These tools were mainly designed to evaluate energy consumption and thermal/lightning performance. The solutions were obtained iteratively through multiple nested solvers which result in numerical errors and discontinuities. Moreover, these tools were developed starting in the 1970's for steady state system balance analysis; for example, the Fortran tool Trynsys became available in 1975. It is only more recently when there has been an

attempt to bridge these legacy tools with dynamics systems for decision making. Within the current toolset there are inadequate notions of continuous-time and hybrid control systems interacting with the building system. Due to these limitations, existing building energy models are not ready to be integrated with control functions to simulate the overall performance and energy consumption of the entire closed-loop system. This gap impedes the development of building control functions and the analysis of energy reduction potentials of retrofitting existing buildings. Moreover, the current toolsets are not well suited to representing complex systems in a manner that easily allows for the understanding of the underlying dynamical phenomena

Research Challenges

- Currently, there is a lack of ability in efficient handling of multi-domain and multiple-time-scale phenomena– including electrical, mechanical, thermal, optical, chemical, and controls for cyber-physical integration.
- There is inadequate high-quality data available for model development, especially for larger buildings.
- Current models do not fully capture all relevant factors such as environmental inputs (disturbances) and the effects of the occupants, including thermal/lightning preference and usage pattern, and their ingress/egress on energy needs and losses.
- The technology path for model validation, model reduction, automated model creation, uncertainty characterization, and integration in design iteration/optimization and control systems is not yet clearly defined. The path needs to be defined jointly by the building modeling community and the control community.
- Comprehensive models that can be used to demonstrate benefits such as net zero energy building, energy saving for retrofits and smart grids do not yet exist.
- Plug-and-play model modules need to be developed to enable cross-disciplinary collaborations and innovations. However, such modules may pose challenges and require breakthrough in numerical and software techniques.
- Renewable power sources and plug-in vehicles are being integrated with buildings to form microgrids. This developing trend has not been incorporated in current-generation building models.

Recommendations

- NSF should consider supporting or facilitating programs to collect quality data helpful for building energy model development. This could mean the establishment of a national user facility such as the NEES model for distributed data gathering for building system simulation under widely varying geographic conditions.
- NSF could work with other government agencies and industrial partners to collect usage data through large scale household monitoring.
- NSF and DOE (Office of Science) should promote the development of current-generation, control-oriented modeling and simulation tool for building systems. This would be a departure from the 1970's vintage Fortran-based tools that are currently state of the art. This includes modeling tools for complex dynamic systems with multiple time scales and large scale human interaction.

- There seems to be significant analogy between building energy systems and other energy systems, such as hybrid vehicles. Knowledge and lessons-learned in those areas can be leveraged through the support of NSF.
- NSF should support research on the microgrid concepts, to clearly understand the impacts and potentials of integrating building energy systems with renewable energy sources and plug-in hybrids.

4B. ESTIMATION/DIAGNOSTICS

Description of the research area

For future buildings, and recent construction, building information management (BIM) tools give access to a lot of information which could be relevant to several types of building models that would be constructed using current state of the art tools (Trynsys, Energy+, etc.). While it was acknowledged in the Modeling working group that these tools are currently lacking, there is at least some current capability. The key challenge to rapid deployment and impact for automation and control for building systems is the fact that the vast majority of buildings in existence today do not have BIM databases. In fact, many buildings do not have any electronic records of their composition or layout. Since buildings have a useful life of decades, it is likely that the lack of capability for forward modeling will remain for the foreseeable future. Therefore, for systems science tools to be of use to buildings, it is critical to be able to examine measurement data from sensor systems and use that to infer the building behavior. This is the estimation problem and it is essential to the retrofit problem which is the highest payoff sector in the building systems space.

The dual to the estimation problem is the diagnostics problem whereby sensor information is used to determine faulty system components and take necessary action.

Technical Challenges

The estimation of building behavior is similar in some respects to the estimation problem for other engineered systems; however, there are some key differences that were identified as major challenges.

- Complexity: There are large numbers of sensors and points of data collection available within buildings. Apart from the practical issues associated with gathering (sensing) and transmitting (communicating) the data, there are analytical issues associated with dealing in large scale information management in real time. The ability to manage this information in an efficient and scalable fashion is critical. This becomes even more critical with the retrofit problem whereby the optimal location of the sensors within a network is part of the overall challenge. The solution paths of centralized or distributed estimation/diagnostics are both available but one is scalable and recyclable whilst the other is not.

- Robustness: Building systems are uncertain environments that are dynamically changing due to external conditions. Moreover, the actual underlying dynamical structure will change over time as building mechanical systems get 'out of tune' or sensors drift/degrade/fail. In a dramatic case, the building system itself is physically reconfigured through additions or remodeling. Anecdotes abounded from practitioners regarding space reorganization such as a dividing wall being unwittingly inserted between a sensor and the air handling unit supplying cooling. It is imperative that any estimation/diagnostic approach be either robust against system changes or, preferably, learn the system changes (i.e. parameters/structure) while it is simultaneously determining the system states.
- Human-in-the-loop: The ability to estimate the physical structure and its behavior for these large complex heterogeneous systems is a challenge as previously mentioned. Performing this identification when a population of individuals is occupying the building is an additional challenge. The key challenge is whether humans-in-the-cyberphysical-loop are to be seen as disturbances or as sensing elements in their own right. This challenge maps back to previously mentioned challenges regarding appropriate models and dynamic constructs that can be used to capture the behavior in a form enabling estimation/diagnostics.

Recommendations:

- Develop scalable robust tools for estimation of large scale complex uncertain systems. These tools could be model-based with a hierarchical structure to handle complexity or they could be unstructured using a purely data-driven machine learning paradigm. Additionally, the tradeoffs between centralized and distributed/local estimation must be created for these systems. In particular, they must be robust to the stochastic and unpredictable nature of wide range of human interaction.
- NSF should work with other agencies or organizations to establish testbeds for estimation on these large scale systems. One promising avenue is the large box store community. They have very well defined and well known system parameters. They are well instrumented. They have redundant geographic coverage allowing for averaging and comparison of results among different units.
- NSF should develop human-in-the-cyberphysical-loop multi-disciplinary programs that focus on understanding human-machine interface (HMI) from a much broader perspective than current IT related computer activities. In particular, we seek to understand how significant populations (100's to 1000's) interact with a dynamic built environment. The first stage would be to identify scalable dynamic modeling paradigms and develop appropriate tools that could be used to support many of the other technical topics considered in this workshop.

4C. COMMUNICATION

Description of Area:

Communication infrastructure is an essential and integral part of the building information and control system. It supports the intra-building information exchange between human users/operators and automation systems (e.g., sensor data for operators to make decisions/monitor, operator command), between sensors (as part of the sensor network), and between sensor and actuators as part of the closed loop control system. It may also involve extra-building communication with utility company and market (pricing information) and renewable sources (generation capacity). There is an emerging building network standard, BACnet, but it is not interoperable with other building information sources and is challenging to configure. Communication infrastructure remains challenging to retrofit to existing buildings.

Research Challenges:

- Building network configuration and maintenance is a labor intensive endeavor. There is a lack of plug-and-play capability such as 802.11x.
- Design, specification and deployment of sensor networks for building control and diagnostic applications are ad hoc, typically optimistic in cost and performance and with no ability to reliably evaluate cost-performance trade-off in the early stage of the design.
- There is a lack of understanding of effective human-machine interfaces that ensure persistent energy efficient building system operation.
- There is a lack of integration and interoperability with building information sources: sensor measurements (thermal, lighting, occupancy, surveillance), building usage schedule, weather data, power distribution, power generation and delivery, security, etc.
- Communication network and sensors use energy too. This lead to research issues on energy harvesting, sensor scheduling, query-based sensing. Some of these issues could involve collaboration with the sensor network community, especially field sensing.

Recommendations:

- Develop Tools for automating the configuration, customization, and deployment of building networks. Key issues to address include: protocol design, reduce field engineering/expert touch, preserve modularity (plug-and-play capability) to enable scalability and extensibility.
- Tools for synthesis and configuration of building sensor networks. Key issues to address include: Wired/wireless sensor network design tailored to specific applications (i.e. control design, diagnostics algorithm) with cost-performance trade-offs. Uncertainties in the built environment should be factored in explicitly. What kind of information/data needs to be collected (how many sensors, what type and where?) to get a robust estimate of the "state of the building" (relevant to a specific application – control, diagnostics)? This is a cross-cutting issue with estimation-diagnostics-control groups, since this involves synthesis of application/information layer as well as implementation/network layer.
- Human-machine interface design. The key issue is how best to communicate information to the user for more "educated decision-making," e.g., what is the best means to be make occupants/operators aware of energy usage so that solutions implemented are not over-ridden or ignored? This is inherently a human factor and

psychology issue, as well as relevance to sociology, since comfort has cultural/socio-economic underpinning. Therefore, collaboration with the HMI community is essential.

4D. CONTROL AND OPTIMIZATION OF BUILDING SYSTEMS

Description of the area:

The control and optimization of efficient building energy consumption is a multi-domain challenge. Buildings are complex systems that vary dramatically in age, size, and materials. In addition to these generalizations, each building has a one-of-a-kind character to its energy utilization while responding to climates in its own unique way. The lack of equipment standardization and the legacy of existing energy utilization subsystems add an uncertainty dimension to this engineering challenge. Consider, for example, the HVAC systems in buildings. These systems can be centralized, decentralized or a hybrid combination of both owing to partial upgrades within a building. In new building projects, there exists a potential for employing a systems engineering approach that can effectively leverage highly advanced control analysis and design tools to robustly improve energy efficiency. However, for the retrofit of existing buildings the avenues of improvements in energy efficiency are much more limited. Common among all of these challenges of building systems is the significant energy improvement while realizing both comfort and safety.

Research challenges:

The fundamental issues associated with the control and optimization of building energy usage include

1. human factors and psychology,
2. scalable robust control and optimization technologies,
3. minimal sensor sets insensitive to location and faults while exploiting new opportunities in virtual sensing, and
4. integration with the electricity grid.

Each of these are explored in more depth in the following:

- Human Factors and Psychology: Many building energy utilization control systems are not operating optimally owing to human-in-the-loop interactions. There is a fundamental disconnect between the user desire and the reference signals available to achieve those desired outcomes. For example, if a building occupant is too hot; their response is to lower the temperature. However if the interface (thermostat) is less quantitative and more qualitative, such as “I am too hot”, a combination of blower speed and A/C compressor operation could be simultaneously specified such that the overall energy consumption is minimized subject to the cooling request. Moreover, a

user education interface should be realized which links their desired energy consumption commands to overall energy usage. Presenting users with an innovative interface will enable both human-machine integration and user education.

- Scalable Robust Control and Optimization Technologies: A general control and optimization approach to building energy utilization requires fundamental advancements in scalable multivariable adaptive control technologies. Such solutions create the enabling technologies for both new and retrofit building solutions. Owing to the large dimensionality of the control and optimization problem, advancements in self-configuring and self-calibration control systems are paramount. Based on the building floor plan, the sub-system may be ordered to produce a block diagonal interconnection. This latter feature allows for a hierarchical control structure where local control loops guarantee robust operation and a supervisory control system provides optimally based coordination of the subsystems.

Beyond the controller design and optimization methods is the hardware realization ranging from sensor technology, to energy transformation subsystems to the sensor/controller communications. Collectively, a systems level fresh-eyes-perspective of all the issues associated with the optimization and control of building energy utilization provides unique opportunities for fundamental discoveries in knowledge. The key areas of research identified during this workshop addressing optimized energy consumption in buildings include the following:

a) **Closed loop behavior of large-scale networks**. The communication technology of today has lead to significant research and advancements in wireless (and wireline) sensor networks. Building systems is the natural application for this technology. However, it is anticipated that significant challenges will emerge concerning the design closed loop systems based on large-scale wireless/wireline networks.

b) **Building controls co-design.** A fundamental challenge to control of building systems is that the control system is usually not taken into consideration when the building is designed. For example, actuators and sensors should be chosen to make building energy utilization both controllable and observable, and building control system design should take advantage of local operating environments such as natural lighting, solar heat gain, wind, etc. In this regards, passive subsystems with adaptive parameters could be developed similar to a variable volume air handling system thereby further allowing the building controllability properties to be tunable.

c) **Closed loop identification and adaptive control for buildings**. In many building applications (especially in retro-fit situations), a control-oriented building model is not available. Although it is possible to implement local control solutions at the subsystems level, the system-of-systems operation will be highly suboptimal. The challenge is to determine the key parameters that can be identified during closed loop to facilitate increasingly better control performance (e.g. in terms of energy consumption and comfort) of the building as the system is operated in days, weeks, seasons and years. Opportunity of significant performance and efficiency gain exist for key

building subsystems including HVAC/R and lighting systems. Methods such as model predictive control, adaptive control and robust control could be fused into the development of an evolutionary learning based control solution, with emphasis on distributed architectures to avoid excessive communication overhead.

d) **Active building envelope control**. A huge potential for improved performance in building energy consumption is anticipated from active or adaptive components that control the energy transmission path between the building and its exterior climate. Nano-technology and materials engineering are viewed as revolutionary technologies for intelligent building façades, windows and roofs. Harvesting energy from the building exterior via solar solutions and wind will further drive materials innovation leading to energy harvesting structural components. The active building envelop will create many new opportunities as well as create significant challenges with regards to the control and optimization of energy transport.

e) **Control of building systems as micro-grids or as Smart Grid components**. Networks of buildings (such as a campus) or an isolated building can be considered as a micro-grid (sometimes having its own power sources). The operational flexibility of (networks of) buildings can offer significant flexibility in grid balancing by exploiting the significant thermal storage possibilities in buildings, where the slow time constants are exploited. In this way, all buildings can easily absorb (negative or positive) power spikes of 5-10 minutes duration, but usually also much longer power transients can be absorbed. For buildings with water-to-air heat pumps, energy can be stored for more than a year. Climate based energy utilization models could also be developed for energy needs forecasting. The forecasting models enable service providers to schedule and prioritize the power needs in advance while also notifying consumers in advance that excessive requested power levels should be reduced.

f) **Control retrofit.** In many existing buildings, the feedback systems are not tuned optimally, are not sufficiently coordinated, or do not exist. The challenges are to identify the modifications with higher potentials, to calculate the saving potentials based on improved control for a specific building, and to document the savings, once a new feedback strategy has been implemented.

<u>Recommendations:</u>

- NSF, potentially in collaboration with other organizations, should establish research initiatives towards massive energy savings solutions based on building systems control.
- Additionally, it is imperative to establish research initiatives towards a new paradigm for designing control systems for buildings that take a holistic but scalable approach.
- Establish research initiatives towards cross-disciplinary activities that cross-fertilize between the systems and controls engineering with other building design stakeholders, e.g. architecture, civil engineering, behavioral psychology, meteorology, etc.

5. DISCUSSION

The primary goals of this workshop were twofold. First, to raise awareness within the controls community as to the suitability of and need for novel control tools in this important domain of societal need. The second goal was to identify key technical challenges, their barriers, and potential paths forward towards solutions. This collection of individuals, and the resulting exchange of information, went a long way towards satisfying these two goals of the workshop. By design, many of the invited participants worked in technical areas outside the general application space of buildings. Consequently the goal of raising awareness for building systems as a worthwhile scientific challenge within the controls community was definitely met for this subset of participants. During the workshop there were several communications among participants as to how their skill sets could be targeted towards buildings systems. Many of the attendees came into the workshop very skeptical of the relevance for their control tools on building systems and also skeptical of buildings as a scientific endeavor in the systems and control space. However, short-term follow up conversations by the organizers have found a high degree of enthusiasm and urgency for action by attendees who had not previously viewed buildings as a scientific challenge. The longer-term follow up to the workshop will include the communication of the workshop results to the larger controls community with the goal of drawing upon additional members of the community to provide their best ideas.

The workshop was also able to point out key technical challenges associated with building systems that our controls community is well positioned to address. Building systems are complex heterogeneous dynamic systems. To control these systems it is imperative to create a scalable modeling architecture that spans the requirements, demands, and constraints of the physical nature of these systems to the level needed for dynamical insight and decision making. Additionally, it is important to develop simulation and analysis tools that are designed to meet the current needs combining computing, communication and decision-making. The current state-of-the-art modeling tools are based on 1970's vintage capabilities. We need new multi-physics tools and toolsets that allow us to span a wide range of physical phenomena, spatial resolution and time scales. Bits and pieces exist today, and Dr. Wetter from LBNL gave an overview of particular Modelica approaches under development in his group. However, there is no large scale concerted effort. Additionally, the modeling in humans interacting with these systems would be a key contribution. If an effort such as the previous NSF NEES activity could be turned towards modeling, simulation and verification for building systems this could be a very valuable enabler.

In addition to forward modeling, it is imperative to determine analytical tools that can extract building system dynamics from available and appropriate sensor information. In particular, these tools must be modular and scalable to allow zone-level or building level or even district/campus level system identification. The tools must also be robust to potential sensing problems, possibly building in redundancy through sensor fusion. As was stated by one workshop participant, "stuff happens and you have to assume some sensor will go bad at some point in time." Large scale complex system interrogation and identification under imperfect or unknown model structure

plus incorrect input information is a tremendous technical challenge that the controls community can address.

Finally, the ability to control these complex systems in a safe and efficient manner is a research challenge well suited to our community. In fact, one participant indicated that buildings may be the 'perfect large scale systems science application' due to the fact that they possess specific structure and are inherently safe in a dynamical sense. Since building energy flow networks are an interconnection of passive subsystems, the overall emergent behavior is much more likely to be stable than other types of large scale systems such as power grids. This gives the control engineers opportunities to be more aggressive in control and optimization designs than other fields. However, as with the case of sensing and identification for complex systems the designed control algorithm must be robust to the inevitable changing of the dynamic environment as well and the sensor failures that will occur.

.

6. CONCLUSIONS AND RECOMMENDATIONS

In conclusion, the participants in the workshop agreed that the challenges are significant; both technically and from a societal viewpoint. They also agreed that it was imperative for NSF to provide scientific leadership in this arena since it was possible for NSF to sponsor and promote longer term basic research in systems theory related to buildings that other organizations could not. The advances in efficiency to be made may necessitate collaboration with other disciplines so as to bring in the multiple facets of the overall building. However, there was consensus among the participants that the controls community can and should take the lead in meeting the challenges

There were several recommendations made in each of the breakout groups but, as with the cross cutting themes, there were some macro-level recommendations that emerged as clear points of focus. First and foremost, it is imperative to establish a large scale cross-disciplinary effort across the country that is focused on building systems science. This will entail multiple disciplines; from controls to civil engineering, behavioral psychology, human factors, economics, etc. However it should be led by the controls community which has the ability to see things from a systems perspective. Secondly, it is critical to replace the current modeling and simulation tools, now 40 years old, with next generation tools. Thirdly, it is necessary to develop or, in some cases, translate scientific tools that are capable of dealing with large scale complex systems that are continuously evolving and also subjected to faults.

A recommended approach to incorporating all of these activities is to develop a network of installations and institutions that is a collection of the best practices and capabilities in each of the areas needed. The network approach is advocated since it may be a distinct challenge for any one institution to create the necessary span of intellectual infrastructure to be successful. For example, there could be a modeling and simulation center that was responsible for developing and deploying the next generation simulation tools. This would be closely tied with a separate center responsible for understanding large scale human-in-the-cyberphysical-loop interactions.

Simultaneously, a third entity (campus, company, national lab etc.) could act as an experimental laboratory gathering data to validate the tools being developed elsewhere. This is a short and non-exhaustive list and there are naturally other entities whose capabilities could be brought to bear. The goal would be to create a virtual center out of several distributed activities where individual best practices could be integrated to both create large scale scientific solutions and, as importantly, drive these solutions into the technical community so that they are accepted. The analog for comparison is the NSF-sponsored George E. Brown Jr. Network for Earthquake Engineering Simulation that tied together several key pieces of scientific infrastructure to create a national research and education resource that created much more than the sum of the parts. A similar construct could be made to work for buildings whereby the best ideas and capabilities could be pooled to create a national infrastructure.

A key question is "Why NSF?" and here we present 2 answers. First of all, NSF has the experience of creating collaboratories among research institutions. The NEES program is but one example, with others being the National Nanotechnology Infrastructure Network, Academic Research Fleet, Aricebo observatory, etc. These Major Multi-User Research Facilities are something NSF has a long track record of establishing and overseeing. The second reason that NSF should take the lead is the long-term view that NSF is afforded for the development of scientific tools and knowledge. Other federal agencies operating in this application domain would not have the same time horizon for the basic research into systems science that NSF would have.

Based on these recommendations and reasoning the organizers urge the NSF leadership to take a bold step towards transforming our national infrastructure. Based on the response from the workshop participants, the systems and controls community stands poised to vigorously participate.

7. ACKNOWLEDGEMENT

The organizers of this workshop would like to thank the National Science Foundation for their support through the award NSF CMMI-1010747. In particular, they would like to thank Suhada Jayasuriya, program manager of the Control Systems Program within CMMI at NSF. They would also like to thank all of the speakers and participants at the workshop for their significant contributions.

8. REFERENCES

[1] Energy Information Administration, Annual Energy Review 2006, Washington, DC, June 2007. Also, http://www.eia.doe.gov.

[2] DOE Report No. DOE/EIA-0573, 2007. Also, http://www.eia.doe.gov/oiaf/1605/ggrpt.

APPENDIX

Workshop participants:

First Name	Last Name	Institution
Andrew	Alleyne	University of Illinois
Anu	Annaswamy	Massachusetts Institute of Technology
Panos	Antsaklis	Notre Dame
Dhiraj	Arora	GE Research
John	Beane	Honeywell
Francesco	Borelli	University of California Berkeley
James	Botic	Johnson Controls Inc.
Jim	Braun	Purdue
Francesco	Bullo	University of California Santa Barbara
Steven	Bushby	National Institute of Standards and Technology
Amit	Chakraborty	Siemens Corporation, Corporate Research
Emmanuel	Collins	Florida State
Geir	Dullerud	University of Illinois
Brian	Fabien	University of Washington
Brian	Fiegan	Trane
Matt	Franchek	University of Houston
Brandon	Hencey	Cornell University
Jungho	Kim	Univesity of Maryland
Miroslav	Krstic	University of California San Diego
Luke	Leung	Skidmore, Owings & Merrill LLP
Colin	McCormick	Department of Energy
Prashant	Mehta	University of Illinois
William	Messner	Carnegie Mellon
Satish	Narayan	United Technologies Corporation
Huei	Peng	University of Michigan
Brian	Rasmussen	Texas A & M
Mario	Rotea	UT Dallas
Sarah	Ryker	Science & Technology Policy Institute
Marty	Savoie	US CoE CERL
Kim	Stelson	University of Minnesota
Jakob	Stoustrup	Aalborg University
Greg	Washington	The Ohio State University
John	Wen	RPI
Michael	Wetter	Lawrence Berkeley National Laboratory
Fumin	Zhang	Georgia Tech

NSF CMMI Workshop on Building Systems

May 24-25, 2010

Monday, May 24, 2010

7:30 -8:00 AM	Continental Breakfast
8:00 - 8:30 AM	Opening Remarks and Overview — A. Alleyne and S. Jayasuriya
8:30 - 9:00 AM	Speaker 1— Colin McCormick (Department of Energy)
9:00 - 9:30 AM	Speaker 2 — Michael Wetter (Lawrence Berkeley National Laboratory)
9:30 - 10:00 AM	Speaker 3 — John Beane (Honeywell Research)
10:00 - 10:30 AM	Speaker 4 —Prashant Mehta (Illinois)
10:30 - 11:00 AM	Break
11:00 - 11:30 AM	Speaker 5 — Steven Bushby (National Institute of Standards and Technology)
11:30 - 12:00 AM	Speaker 6 — Jim Braun (Purdue)
12:00 - 1:00 PM	Lunch and preliminary discussions
1:00 – 1:30 PM	Speaker 7 — Luke Leung (Skidmore Owings & Merrill)
1:30 - 2:00 PM	Speaker 8 — Amit Chakraborty (Siemens Research Center)
2:00 - 2:30 PM	Break
2:30 - 3:00 PM	Orientation for working group meetings
3:00 - 5:00 PM	Working group meetings 1 (Assigned groups)
5:30 - 6:00 PM	Reception, Grainger Engineering Library
6:00 - 8:00 PM	Dinner, Grainger Engineering Library, West Lounge (2nd floor)

Tuesday, May 25

8:00 – 8:30 AM	Continental Breakfast
8:30 – 10:00 AM	Working group meetings II (Assigned groups)
10:00 – 10:30 AM	Break
10:30– 11:30 AM	Preliminary Report synthesis and preparation
11:30 - 1:30 PM	Working Lunch Report presentations and general discussion
1:30 PM	Workshop adjourns
1:30 - 5:00 PM	Initial report writing by Advisory Board. Start to outline report and issue initial writing assignments issued.

Andrew Alleyne, University of Illinois

Andrew Alleyne earned his BSE in mechanical/aerospace engineering from Princeton University, and his MSE and PhD in mechanical engineering from University of California at Berkeley. He joined mechanical engineering faculty at Illinois in 1994, and he was named the Ralph M. and Catherine V. Fisher Professor in 2002. He currently serves as the Associate Dean for Research in the College of Engineering.

Prof. Alleyne's research addresses a range of issues within controls: the analysis and design of control systems in a dimensionless framework, advanced motion control through iterative learning control and adaptive feedforward techniques, and robust control approaches to gain-scheduling as they relate to energy systems and fluid power.

John Beane, Honeywell Research

John Beane is the research manager for Knowledge Services in the Honeywell Automation and Controls Solutions Lab. Honeywell is a global leader in the energy space. Honeywell is working closely with the utilities to develop cost-effective ways to connect homes and buildings to the Smart Grid. Related research topics include: wind farm CBM, predicting wind output, optimizing sources and loads to manage a building microgrid, home energy manager, ADR for buildings and homes, energy data visualization, using data to change human behavior, smart grid communications standards, building energy modeling and simulation, building energy efficiency, mobile tools for building operations and BIM.

Jim Braun, Purdue University

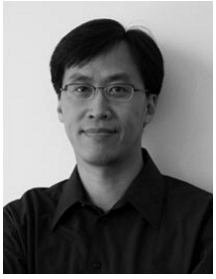
Dr. Braun has worked in the field of air conditioning and refrigeration for over 30 years in both university and industrial settings. His practical experience includes working as a development engineer for advanced cooling equipment, a software developer for simulation tools in modeling buildings and large-scale heating and cooling plants, a developer of intelligent control algorithms for large commercial energy management and control systems, and group manager for controls research. He has been awarded four patents. His research combines the use of computer modeling, optimization, and experiments to study and improve the performance of thermal systems. Overall, Dr. Braun has led or been involved with proposals leading to research awards totaling over $20 million and has over 200 papers journal and conference papers published or in review, five of which received best paper awards. Within ASHRAE, Dr. Braun has been chairman of technical committees on “Smart Building Systems” and “Building Operation Dynamics” and is currently Vice-Chair for the Research Administration Committee. He is an Associate Editor for the International Journal of HVAC&R Research. He is a Fellow within ASHRAE and has received the ASHRAE Distinguished Service Award, the E.K. Campbell Award of Merit, in recognition of outstanding service and achievement in teaching and/or research in subjects relating to the industry and professions represented by ASHRAE, and the Early Achievement Award from the International Building Performance Simulation Association.

Steven Bushby, National Institute of Standards and Technology

Mr. Bushby is the leader of the Mechanical Systems and Controls Group and the Embedded Intelligence in Buildings Program in the Building and Fire Research Laboratory at the National Institute of Standards and Technology. He is responsible for overseeing research activities related to the development of national and international standards for integrated building automation systems, automated fault detection and diagnostics for HVAC system components, automated commissioning tools for HVAC control systems, integration of building control systems with the Smart Grid, and developing a testbed for studying the interaction of multiple building control systems in "cybernetic" buildings.

Amit Chakraborty, Siemens Research Center

Dr. Amit Chakraborty leads the Data Modeling and Optimization Program at Siemens Corporate Research. He received his PhD in Electrical Engineering from Yale University. Prior to that, he obtained his MS and M.Phil in Electrical Engineering also from Yale and his B.Tech in Electronics and Electrical Communication Engineering from the Indian Institute of Technology. He joined Siemens Corporate Research right after his PhD 1996 as a Member of Technical Staff, was subsequently promoted to a Project Manager then to a Senior Member of Technical Staff and to a Program Manager, a position he has held since 2005 to lead the Data Modeling and Optimization program. With a team of 35-40 research scientists, engineers and students, the program focuses primarily on Data Mining and Optimization applications across all three sectors in Siemens, Industry, Healthcare and Energy. He has successfully led several Research and Development projects in Energy Management such as Total Plant Optimization for High Performance Buildings, Parametric Fault Diagnostics for Gas Turbines, Power Flow Optimization for Electric Grids, Semantic Data Modeling for Power Systems etc. His team is also engaged in a several large government R&D projects in collaboration with leading universities. Dr. Chakraborty has mentored many employees, and PhD and Masters students. He has 15 granted and many more pending patents and has also published in respected journals and conferences.



Luke Leung, Skidmore Owings & Merrill

As Associate Director and leader of the Sustainable Engineering Studio, Luke Leung is responsible for systems design and specifications from conception to construction for many commercial and institutional projects including Burj Khalifa, the world's tallest building. He has designed many LEED® projects, ranging from certified to LEED® Platinum, including the second largest LEED® certified building, McCormick Place West.

Colin McCormick, Department of Energy

Dr. Colin McCormick is a Senior Technical Advisor to the Assistant Secretary of Energy Efficiency and Renewable Energy at the Department of Energy. Prior to joining the Department he was an energy and security analyst at the Federation of American Scientists, a staff member with the House Science and Technology Committee, and a AAAS Congressional Fellow on the staff of Rep. Ed Markey of Massachusetts. Dr. McCormick received his PhD in atomic and optical physics from the University of California, Berkeley, and did post-doctoral work in quantum optics at the National Institute of Standards and Technology (NIST) in the group of 1997 Physics Nobel Laureate William Phillips.

Prashant Mehta, University of Illinois

Prashant Mehta is an Assistant Professor at the Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign. He received his Ph.D. in Applied Mathematics from Cornell University in 2004. Prior to joining UIUC, he was a Research Engineer at the United Technologies Research Center (UTRC). His research interests are at the intersection of dynamical systems and control theory, including fundamental limitations in nonlinear control, model reduction of Markov chains, phase transition and learning in large population games.

Prashant Mehta received the Outstanding Achievement Award at UTRC for his contributions to modeling and control of combustion instabilities in jet-engines. His students received the Best Student Paper Award at the IEEE Conference on Decision and Control 2007 and 2009.

Michael Wetter, Lawrence Berkeley National Laboratory

Michael Wetter is a Computational Scientist in the Simulation Research Group at Lawrence Berkeley National Laboratory (LBNL). His research includes integrating building performance simulation tools into the research process, as well as their use for design and operation of buildings. At LBNL, he is developing the Modelica Buildings library for building energy and control systems, the Building Controls Virtual Test Bed software for co-simulation and model-based operation, and the GenOpt optimization program. Prior to joining LBNL, he led the development of building system models at the United Technologies Research Center (UTRC). He did his dissertation at the University of California at Berkeley and at LBNL, where he created the GenOpt optimization program and the BuildOpt building simulation program and where he developed the first building energy optimization technique that provably converges to the optimal building design. He is a recipient of the bi-annual Outstanding Young Contributor Award of the International Building Performance Simulation Association (IBPSA), the vice president of IBPSA-USA and a member of ASHRAE.

NSF CMMI Workshop on Building Systems

E N G I N E E R I N G A T I L L I N O I S

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

Welcome

- We gratefully acknowledge the support from the National Science Foundation
  - CMMI
  - PM Jayasuriya

- We hope it will be an exciting and productive workshop

E N G I N E E R I N G A T I L L I N O I S

Participants

- 35 people
  - Smaller number chosen to focus discussions
- Mix of academia and industry and government
- 1 person per organization
- Mix of “Buildings” and “Non-buildings” personnel
- Breadth of input to the discussions

ENGINEERING AT ILLINOIS

Workshop Goals

- Two main goals for this workshop
- Raise Awareness
  - Longer time scale
  - Make Buildings the next “Vehicle Swarm” application for Controls community

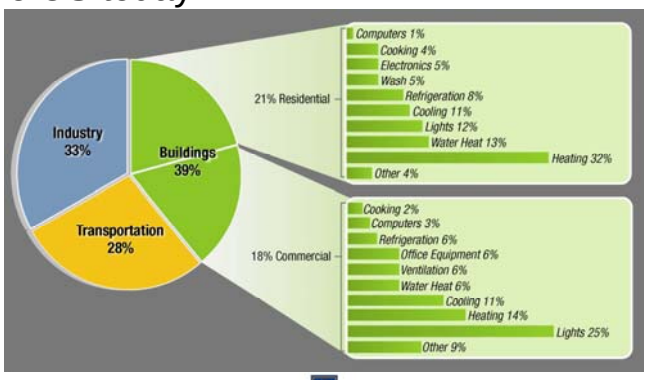
Focus on: Building Science

- Set Directions
  - Shorter time scale
  - Identify key research topics to be initiated now to enable future breakthroughs

ENGINEERING AT ILLINOIS

Current State

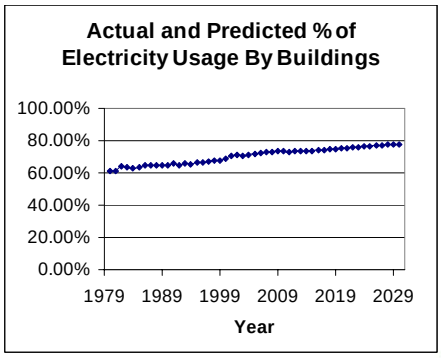
- Buildings use 40% of the total energy consumed in the US today.



E N G I N E E R I N G A T I L L I N O I S

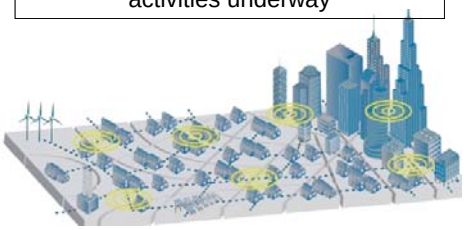
Past, Current, and Future State

- For electricity, it is more severe
  - By 2030, 80% of our electricity will be consumed by buildings



Bldgs Energy Data Book

Unknown impact on the Smart Grid development and deployment activities underway



E N G I N E E R I N G A T I L L I N O I S

Current State

We will nurture a system integration approach to building design, aided by computer tools with embedded energy analysis. It was the system integration of the automobile engine, transmission, brakes and battery that enabled Toyota to create the Prius. With computer control of ignition timing and fuel mix, today's automobile engines operate at 20 percent higher efficiency. **With computer monitoring and continuous, real-time control of HVAC systems, lighting, and shading, far more spectacular efficiencies can be realized in buildings.** There is a growing realization that we should be able to build buildings that will decrease energy use by 80 percent with investments that will pay for themselves in less than 15 years.

Secretary Steve Chu, CalTech Commencement, 2009

ENGINEERING AT ILLINOIS

Current State

- DoE
  - ARPA-E Solicitation
  - Innovation Hubs (ERIC)
  - Interestingly, no EFRC activity to date
    - Perhaps DoE doesn't see this as scientific as Batteries?
- NSF
  - EFRI topic specific to buildings
- Much of the building work ongoing focuses on current/near-term technology
- What new controls-relevant tools need to be developed to enable breakthroughs?
  - >10 year horizon

Several Recent Funding Initiatives

ENGINEERING AT ILLINOIS

Current Challenges

- Complexity
- Constraints
- Stochasticity
  - Weather
  - Pricing
  - People
- Variability and uncertainty
  - Buildings change over time
- What tools can our research community provide?

Yang/Yamazaki Blgd
- 2370 HVAC measurements
- 1 min sample time

ENGINEERING AT ILLINOIS

Current Challenges

- Complexity
- Constraints
- Stochasticity
  - Weather
  - Pricing
  - People
- Variability and uncertainty
  - Buildings change over time

Siebel Center
- Dampers

ENGINEERING AT ILLINOIS

Current Challenges

- Complexity
- Constraints
- Stochasticity
  - Weather
  - Pricing
  - People

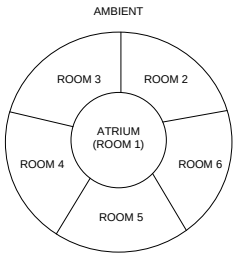
Simple Example

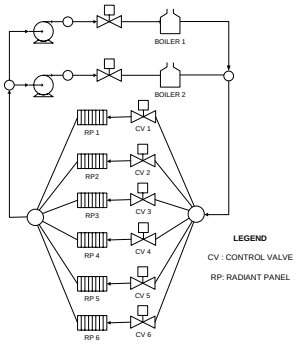
- Variability and uncertainty
  - Buildings change over time

E N G I N E E R I N G A T I L L I N O I S

Current Challenges

- Complexity
- Constraints
- Stochasticity
  - Weather
  - Pricing
  - People



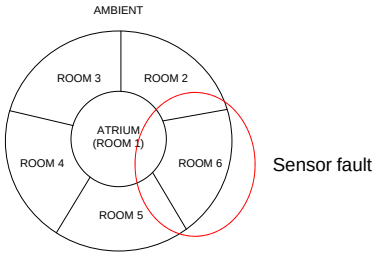


- Variability and uncertainty
  - Buildings change over time

E N G I N E E R I N G A T I L L I N O I S

Current Challenges

- Complexity
- Constraints
- Stochasticity
  - Weather
  - Pricing
  - People



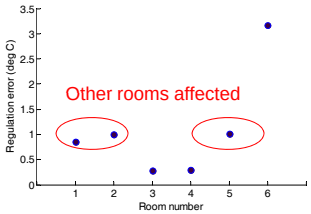
- Variability and uncertainty
  - Buildings change over time

E N G I N E E R I N G A T I L L I N O I S

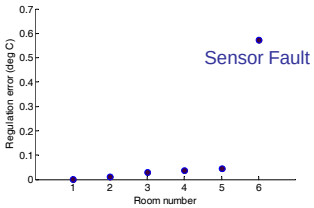
Current Challenges

- Complexity
- Constraints
- Stochasticity
  - Weather
  - Pricing
  - People

Centralized MPC



Decentralized PI



- Variability and uncertainty
  - Buildings change over time

E N G I N E E R I N G A T I L L I N O I S

Current Challenges

- Complexity
- Constraints
- Stochasticity
  - Weather
  - Pricing
  - People
- Variability and uncertainty
  - Buildings change over time
- What tools can our research community provide?

ENGINEERING AT ILLINOIS

Technical Aspects

- Modeling
- Estimation/Diagnostics
- Communication
- Optimization and Control/Decision-Making

These are the 4 main topical areas we will address in this workshop

ENGINEERING AT ILLINOIS

Workshop Agenda

Time	Activity
8:00 - 8:30 AM	Opening Remarks and Overview A. Alleyne and S. Jayasuriya
8:30 - 9:00 AM	Speaker 1—Colin McCormick (Dept of Energy)
9:00 - 9:30 AM	Speaker 2—Michael Wetter (LBL)
9:30 - 10:00 AM	Speaker 3 – John Beane (Honeywell Research)
10:00 - 10:30 AM	Speaker 4—Prashant Mehta (UIUC)
10:30 - 11:00 AM	Break
11:00 - 11:30 AM	Speaker 5—Steven Bushby (NIST)
11:30 - 12:00 AM	Speaker 6—Jim Braun (Purdue)
12:00 - 1:00 PM	Lunch and preliminary discussions
1:00 – 1:30 PM	Speaker 7—Luke Leung (Skidmore Owings & Merrill)
1:30 - 2:00 PM	Speaker 8—Amit Chakraborty (Siemens Research Center)
2:00 - 2:30 PM	Break
2:30 - 3:00 PM	Orientation for working group meetings
3:00 - 5:00 PM	Working group meetings – I (Assigned Groups)
6:00 – 8:00 PM	Dinner and continued discussion.

ENGINEERING AT ILLINOIS

Workshop Agenda

Time	Event
8:30 – 10:00 AM	Working group meetings – II (Assigned Groups)
10:00 – 10:30 AM	Break
10:30– 11:30 AM	Preliminary Report synthesis and preparation
11:30 - 1:30 PM	Working Lunch Report presentations and general discussion
1:30 - 5:00 PM	Draft report writing by Advisory Board

ENGINEERING AT ILLINOIS

Presentations

- Variety of technical areas
- Variety of presenter backgrounds
  - Industry, Academia, Government
- Presentation goals are two fold
  - Set the stage by providing technical context & insight
  - Raise questions to stimulate thoughtful discussion
- Questions to be further examined in the breakout sessions

ENGINEERING AT ILLINOIS

Breakout Sessions

- There will be 2 separate breakout sessions
  - 1st day afternoon and 2nd day morning
- Select a session lead who will guide discussion and communicate the results back to the rest of the workshop
  - There will be projectors in the breakout rooms for your use
  - Scribe will be there as well to capture discussion
- Dinner will provide further opportunity for discussion

ENGINEERING AT ILLINOIS

Reporting

- Lunch report on day 2
  - Presentation to rest of the workshop by each breakout area
- Desired outcomes
  - Cogent and concise report
  - Focus on setting longer term research directions
  - Avoid a laundry list without context or prioritization
- Time is given on day 2 for synthesizing and assembling presentation reports but they can be started on day 1

ENGINEERING AT ILLINOIS

Reporting

- Advisory Committee will:
- Work on expanding the report after the initial presentations
- Start writing assignments
- Leave with a draft report in place

ENGINEERING AT ILLINOIS

Conclusions

- Thank you for joining us
- We value your ideas
- Enjoy the rest of the workshop

ENGINEERING AT ILLINOIS

Building Modeling and Simulation to Support Controls Design and Operation

Michael Wetter
Simulation Research Group
Building Technologies Department
Energy and Environmental Technologies Division
Lawrence Berkeley National Laboratory

May, 2010

1

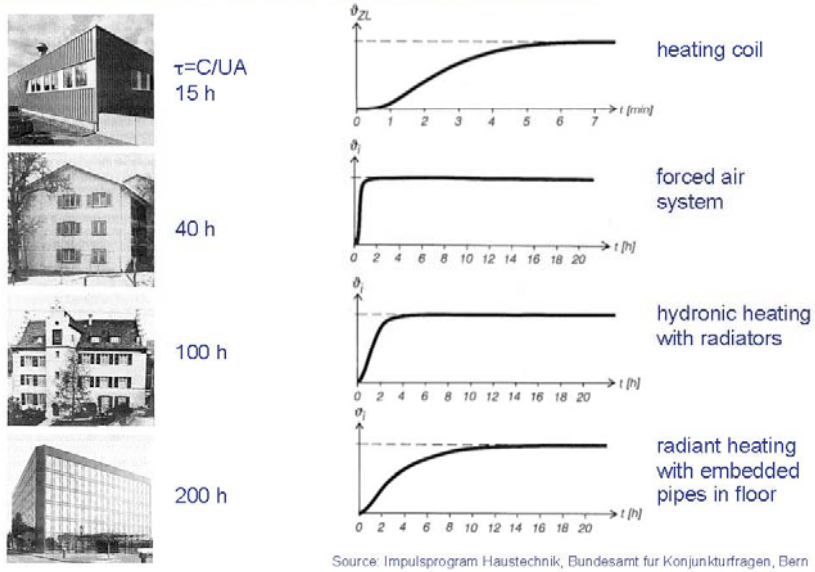
Overview

- Introduction
- Current State
- R&D

2

Introduction – Building Dynamics

Time constants in buildings vary by several orders of magnitudes



Source: Impulsprogram Haustechnik, Bundesamt fur Konjunkturfragen, Bern

Introduction – Building Dynamics

Disturbances become increasingly important

1st order approximation to building temperature

$$\frac{dT}{dt} = \frac{K}{C}(T_\infty - T) + \frac{1}{C}\dot{Q}_d + \frac{1}{C}u \qquad \tau = \frac{C}{K}$$

Old buildings

$K \nearrow$

$\dot{Q}_d \searrow$

Approximate equation

$$C\frac{dT}{dt} = K(T_\infty - T) + u$$

New, low energy buildings

$K \searrow$

$C \nearrow$

$\tau \nearrow$

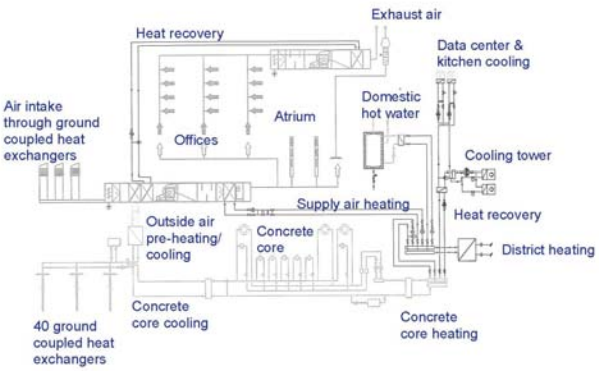
Approximate equation

$$C\frac{dT}{dt} = \dot{Q}_d + u$$

Trends in Building Systems

Building systems become more complex

- Interaction: Continuous time, discrete time, events.
- States: Multiple operating modes.
- Controls integration: Floating setpoints, electrical grid, active façade.
- Thermal integration: Geothermal systems, heat storage and recovery.



	Number of modes
Cooling "generation"	4
Heating "generation"	4
Space cooling	3
Space heating	3
Ventilation	2

5

Source: Oehler, Grosse Passivhaeuser, Kohlhammer, 2004

Introduction – Today's "Building Controls"

ASHRAE Standard Sequences of Controls

Expert opinions determine what is considered a good control sequence
- few conclusive measurements for whole buildings
- lack of simulation capabilities

Typical building design process

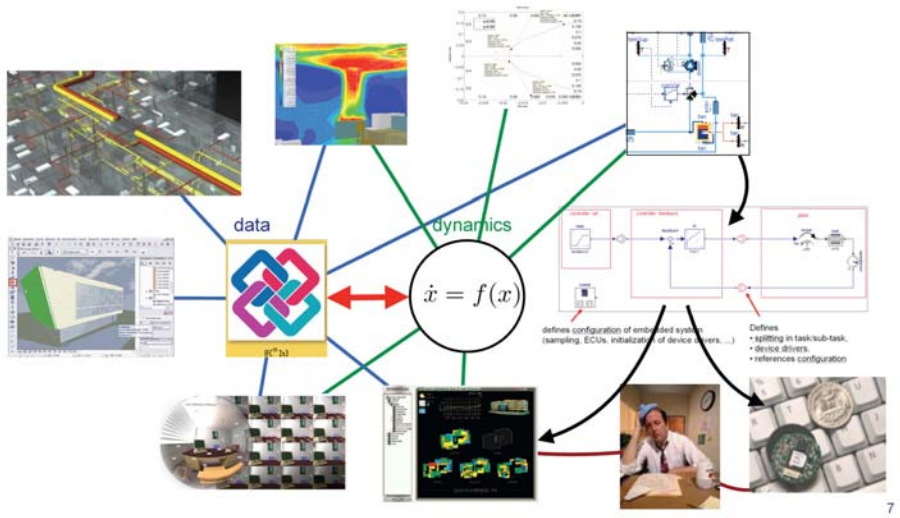
1. HVAC Consultant *may* specify control sequence in English-language.
2. Controls engineer implements some variant of this control sequence.
3. Commissioning agent tests a subset of the control sequence.

There is no verification during design,
the specification is not executable,
the implementation is error-prone,
the commissioning tests only a partial range of the operation.

Few building control systems work as intended.

R&D Needs for Whole-Building Model-Based Design and Operation

What modeling framework enables model-based design and operation?



7

Overview

- Introduction
- Current State
- R&D

8

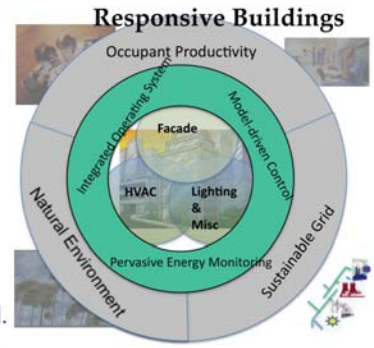
Challenges -- Controls

Integration of subsystems (grid, HVAC, active facade, lighting).

Enable optimal
- energy storage
- equipment scheduling
- setpoint scheduling
- grid interaction.

Making inefficiencies visible to end-user.

Detect and diagnose faults at the system-level.



Close disconnect between design and operation, using executable specification, to
- increase productivity.
- reuse design across platforms.
- enforce accountability across hand-off points.
- reduce human error.

9

Current State -- Building Simulation to Support Controls Design and Operation

Today's building simulation programs (EnergyPlus, DOE-2):

These tools have not been designed to support controls.

Large simulators (500,000 lines of code).

Dynamic models
Heat transfer (opaque constructions & room air).
Energy storage in water tanks.

Steady-state models
HVAC components and system (written for 10 minutes to 1 hour time step).
Controls.

Controls semantics
"Ideal controller" that meets load (cooling power etc.) by computing how much mass flow and what temperature a component needs to deliver, subject to capacity constraints.
No notion of continuous time systems or hybrid systems.

Solution method
10 to 20 nested solvers, no global error control, many components integrate their own solver, which introduces large discontinuities in approximate transfer function.

10

Challenges -- Building Simulation to Support Controls Design and Operation

Express models in a modeling language, not a programming language!

Modular objects with standard interfaces (thermodynamics, controls, ...)

Hierarchies to manage complexity vertically and horizontally

Code generation for control hardware

Different evolutions within modules

- continuous time (seconds to minute time scale)
- discrete time
- finite state machine

Model feedback control of measured states (temperature, pressure), not heating/cooling load. (This requires models and solvers that are different from today's standard building simulation.)

Analysis support through application programming interfaces (API)

- Building Information Models
- link to domain-specific tools (such as MATLAB/Simulink)
- reduced order model extraction
- optimization

11

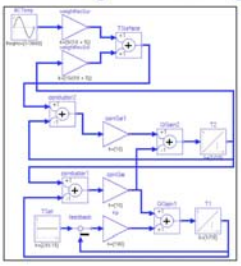
Increase Level of Abstraction

Higher-level of abstraction to

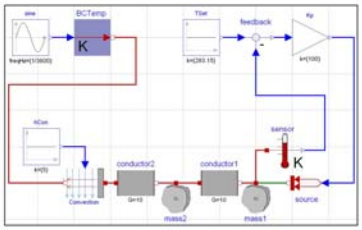
- increase productivity
- facilitate model-reuse
- preserve system topology
- enable analysis
- generate code for target hardware

Procedural modeling ≈ 1970

Block diagram modeling ≈ 1990



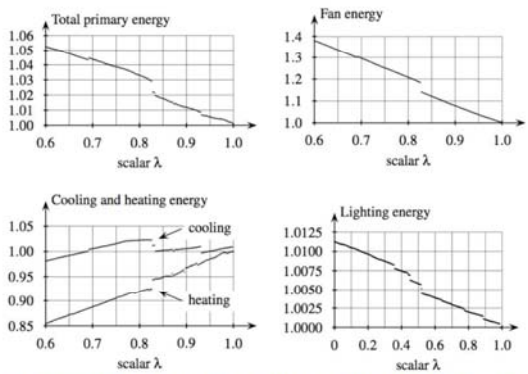
Equation-based, object-oriented modeling ≈ 2000

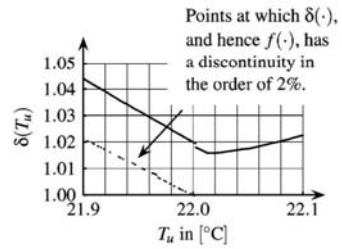


12

Numerical "Noise" in EnergyPlus

$x(\lambda) = x_{HJ} + \lambda\,(x_{sGA} - x_{HJ}),$
$x \in \Re^{13}$





Discontinuities are caused by nested solvers with low precision.
(20+ nested solvers spread over 500,000 lines of code.)

13
Source: Wetter and Wright, 2004

Overview

- Introduction
- Current State
- R&D

Guiding Principles
- scale up to large systems
- open source to get acceptance at ASHRAE
- leverage advances and investments of other industrial sectors
- build on, or establish, standards to avoid fragmentation

14

Separation of Concerns

Modeling **Compilation** **Simulation**

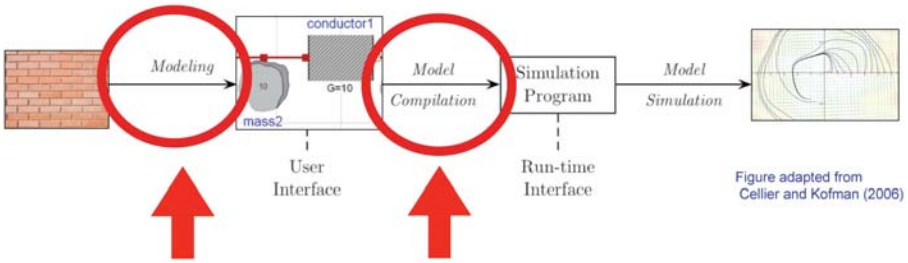


Figure adapted from Cellier and Kofman (2006)

Different coupled domains
- heat transfer
- thermodynamics
- airflow
- controls
- batteries...

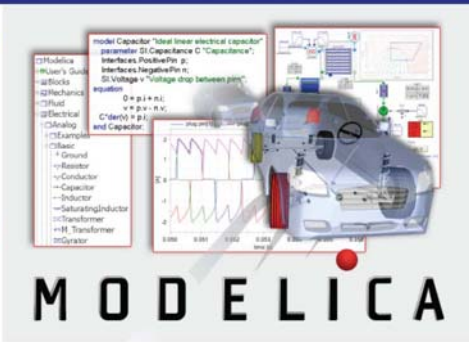
Different states
- continuous time
- discrete time
- finite state machine

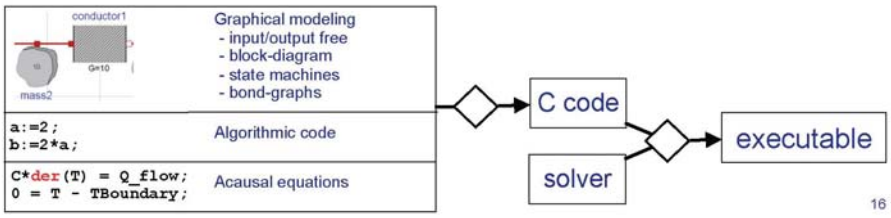
Different code
- simulation
- real-time simulation
- optimization w. analytic gradients

15

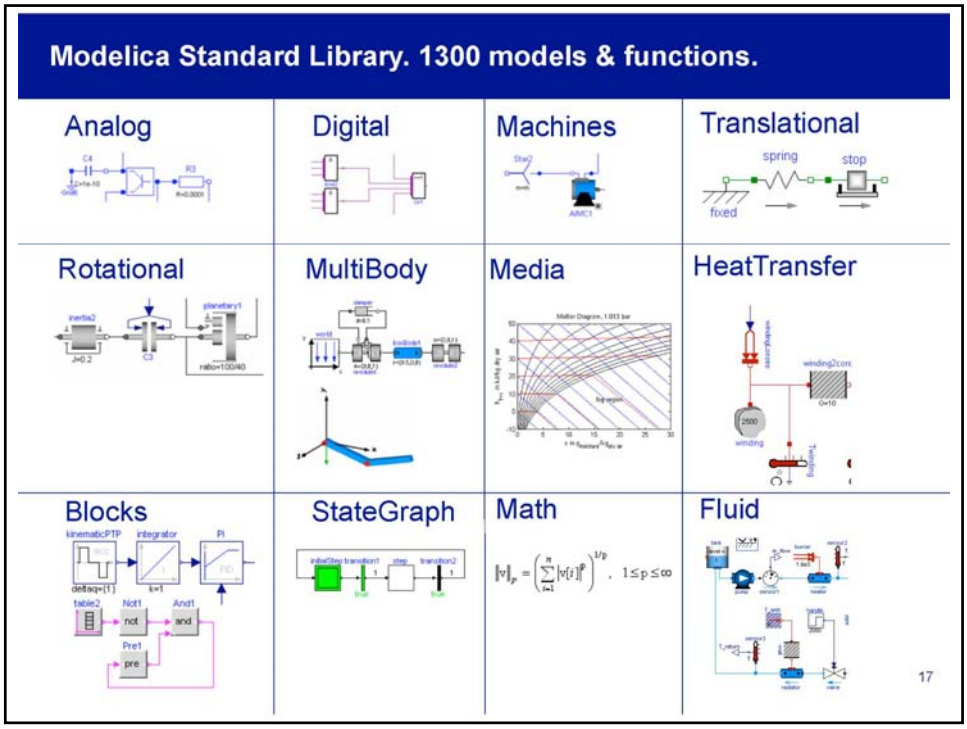
What is Modelica?

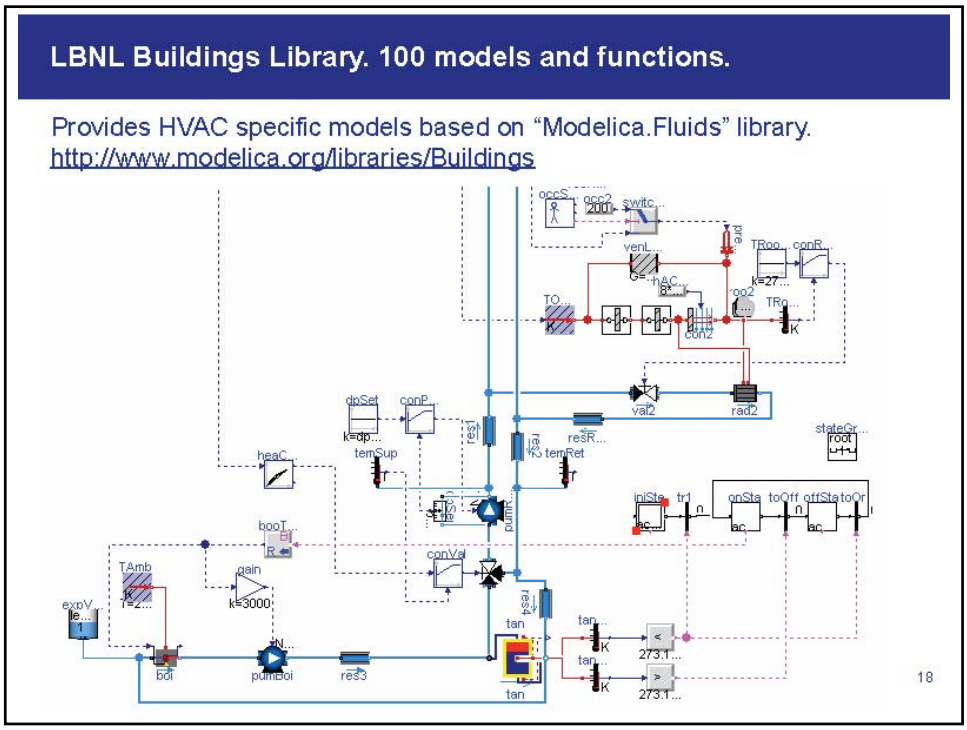
- Object-oriented equation-based modeling language
- Open standard
- Developed since 1996 because conventional approach for modeling was inadequate for integrated engineered systems
- Well positioned to become de-facto open standard for modeling multi-engineering systems
  - ITEA2: 370 person years investment over next three years.





16

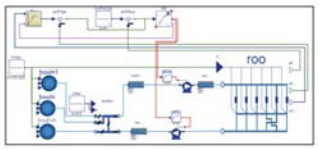

Modelica Standard Library. 1300 models & functions.
Analog
Digital
Machines
Translational
spring
stop
fixed
Rotational
MultiBody
Media
HeatTransfer
Blocks
StateGraph
Math
Fluid
17


LBNL Buildings Library. 100 models and functions.
Provides HVAC specific models based on "Modelica.Fluids" library.
http://www.modelica.org/libraries/Buildings
18

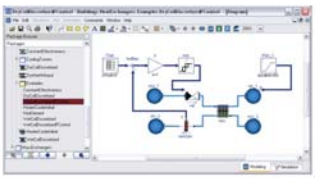
Example Applications

1) Rapid prototyping (13,000 equations)
Reproduced trends published by manufacturer for novel hydronic heating system with radiator pumps and hierarchical system controls. Developed boiler model, radiator model, simple room model and both system models in one week.

2) Supervisory controls (4,400 equations)
Stabilized control for variable air volume flow "trim and response" sequence and reduced energy by solving optimization problem with state constraints.



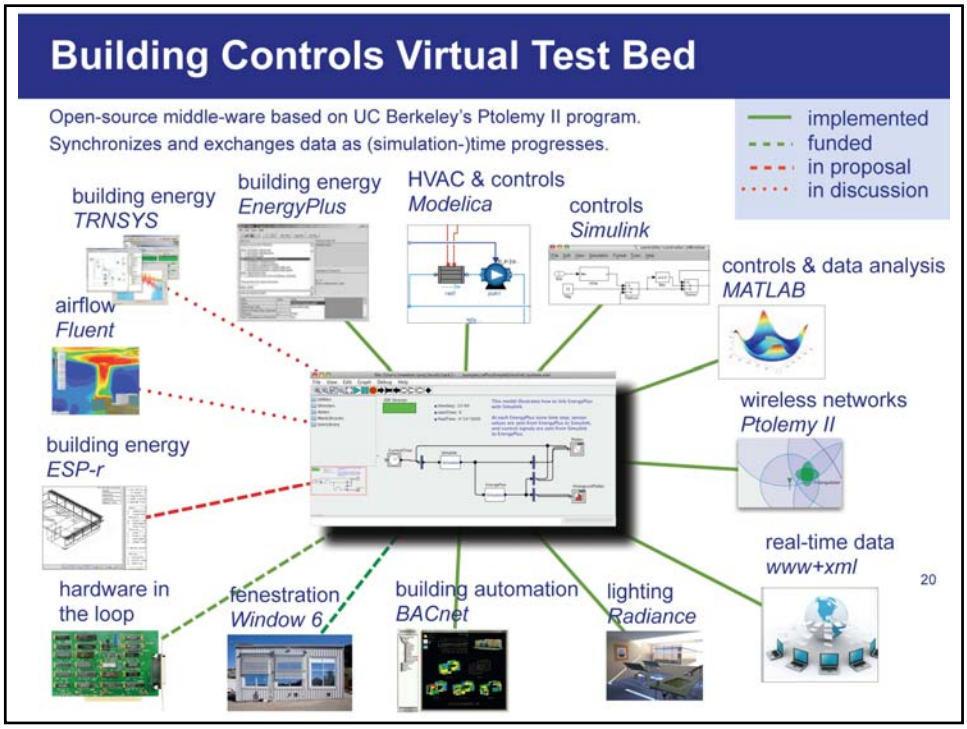
3) Local loop controls (2,600 equations)
Reused high-order non-linear model for controls design in frequency domain to stabilize closed loop control.



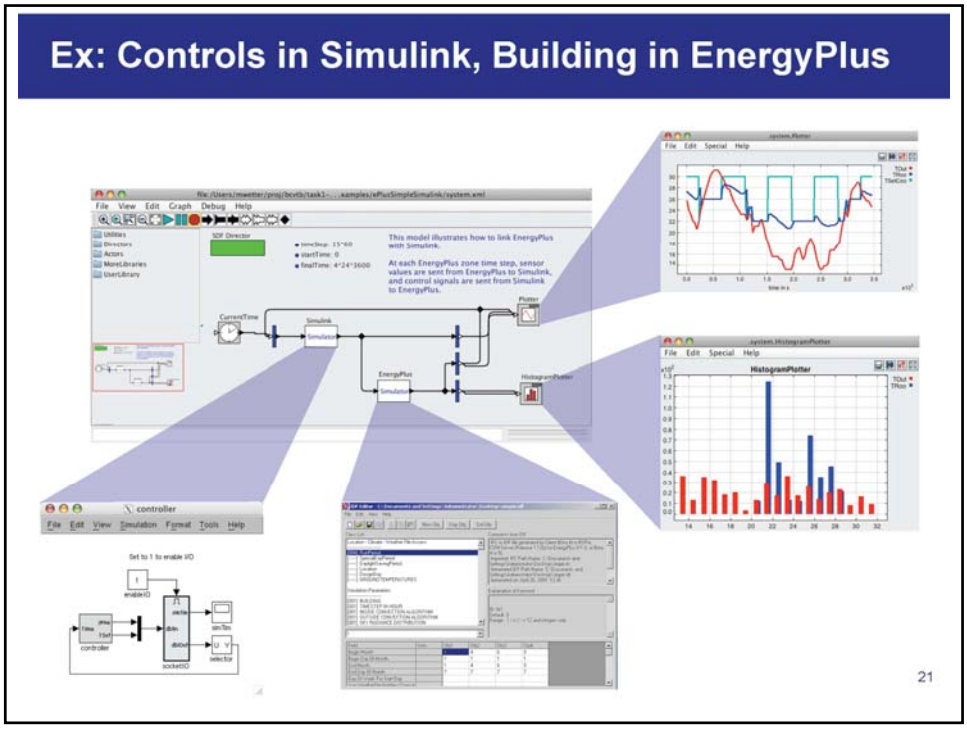
19

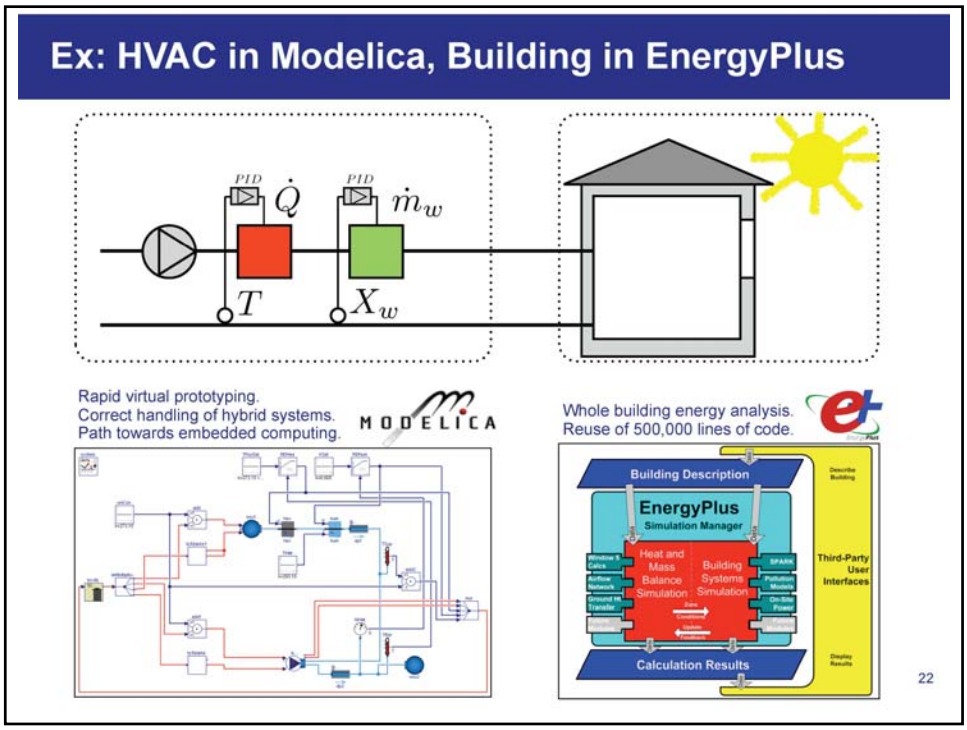
Building Controls Virtual Test Bed

Open-source middle-ware based on UC Berkeley's Ptolemy II program.
Synchronizes and exchanges data as (simulation-)time progresses.

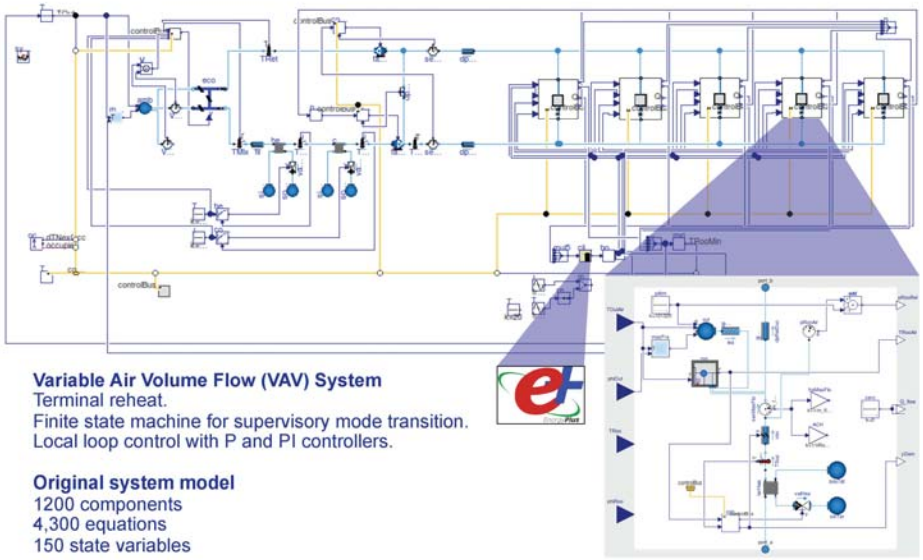


20


Ex: Controls in Simulink, Building in EnergyPlus
This model illustrates how to link EnergyPlus with Simulink.
At each EnergyPlus zone time step, sensor values are sent from EnergyPlus to Simulink, and control signals are sent from Simulink to EnergyPlus.
HistogramPlotter
controller
21


Ex: HVAC in Modelica, Building in EnergyPlus
PID
PID
$\dot{Q}$
$\dot{m}_w$
T
X_w
Rapid virtual prototyping.
Correct handling of hybrid systems.
Path towards embedded computing.
MODELICA
Whole building energy analysis.
Reuse of 500,000 lines of code.
Building Description
EnergyPlus
Simulation Manager
Heat and Mass Balance Simulation
Building Systems Simulation
Calculation Results
Third-Party User Interfaces
22

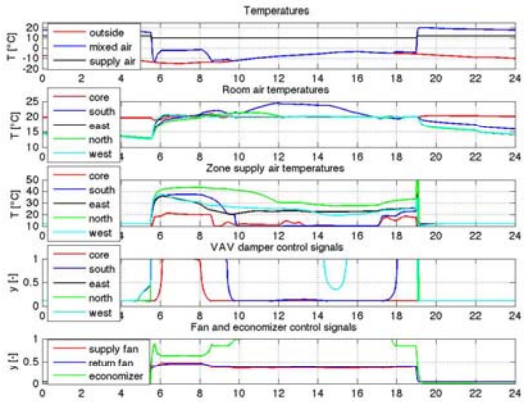
Modelica Implementation of VAV System with ASHRAE Standard Sequence of Controls, linked to EnergyPlus DOE Benchmark Bldg.



Variable Air Volume Flow (VAV) System
Terminal reheat.
Finite state machine for supervisory mode transition.
Local loop control with P and PI controllers.

Original system model
1200 components
4,300 equations
150 state variables

Modelica Implementation of VAV System with ASHRAE Standard Sequence of Controls, linked to EnergyPlus DOE Benchmark Bldg.



The biggest risk for adoption is the lack of robustness of numerical solvers for these DAE systems with continuous and discrete state variables.

Can execute realistic supervisory and local loop control in Modelica linked to EnergyPlus through co-simulation.

R&D Needs:
Robustness of DAE solver.

Support for rapid virtual prototyping.

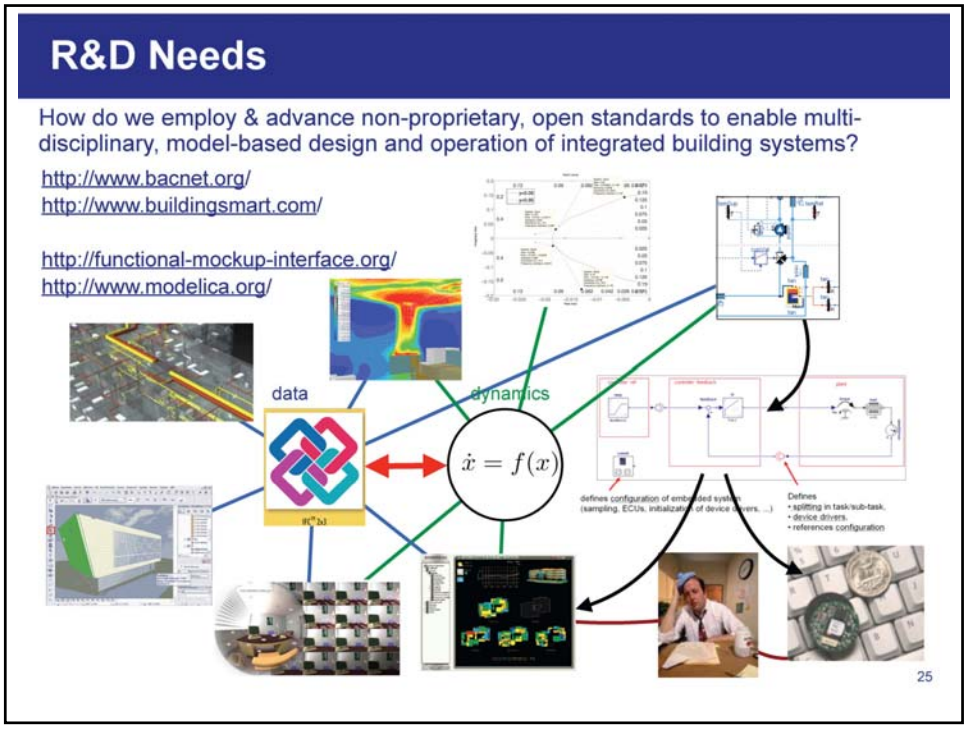
Computing time.

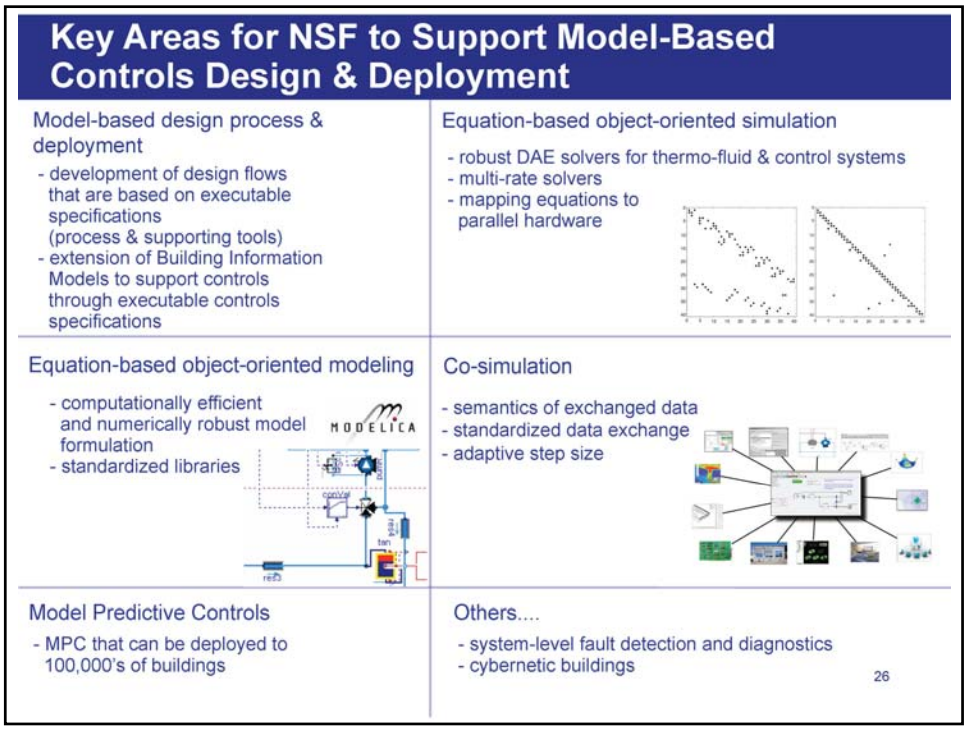
"Packaging" to make technology easier accessible to non-experts.

Scope of validated model library (HVAC & control components and systems).

Code generation to link design to operation.

24


R&D Needs
How do we employ & advance non-proprietary, open standards to enable multi-disciplinary, model-based design and operation of integrated building systems?
http://www.bacnet.org/
http://www.buildingsmart.com/
http://functional-mockup-interface.org/
http://www.modelica.org/
data
dynamics
$\dot{x} = f(x)$
25


Key Areas for NSF to Support Model-Based Controls Design & Deployment
Model-based design process & deployment
- development of design flows that are based on executable specifications (process & supporting tools)
- extension of Building Information Models to support controls through executable controls specifications
Equation-based object-oriented simulation
- robust DAE solvers for thermo-fluid & control systems
- multi-rate solvers
- mapping equations to parallel hardware
Equation-based object-oriented modeling
- computationally efficient and numerically robust model formulation
- standardized libraries
MODELICA
Co-simulation
- semantics of exchanged data
- standardized data exchange
- adaptive step size
Model Predictive Controls
- MPC that can be deployed to 100,000's of buildings
Others....
- system-level fault detection and diagnostics
- cybernetic buildings
26

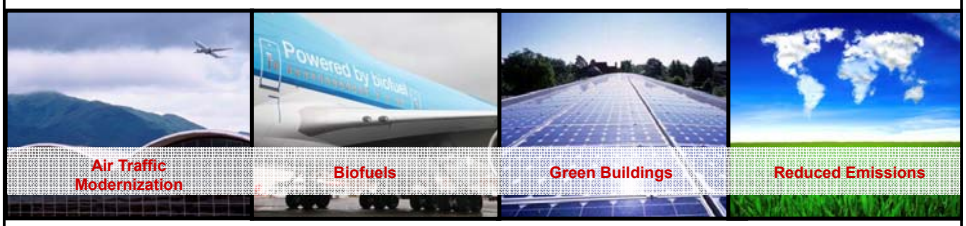
NSF CMMI Workshop on Building Systems

Honeywell Energy Research

May 24-25, 2010

Honeywell

Honeywell



Nearly 50% of Honeywell's product portfolio is linked to energy efficiency. The U.S. could reduce its energy consumption 15 – 20% by immediately and comprehensively adopting existing Honeywell technologies.

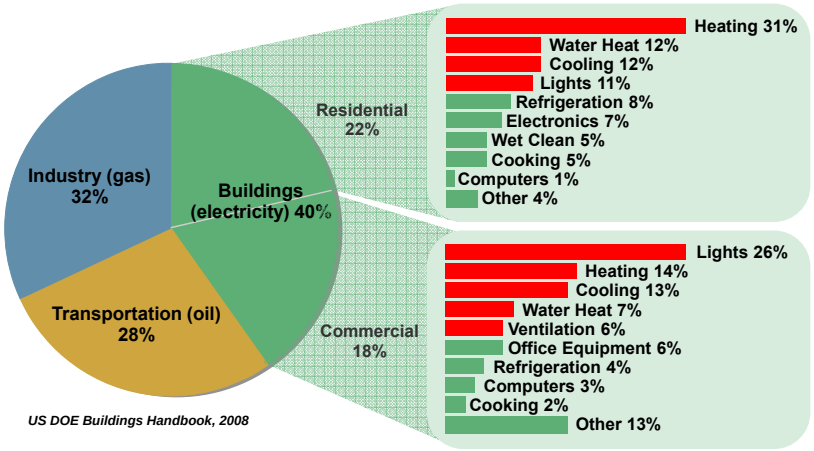
Creating sustainable jobs today using existing technology and infrastructure

2

May 24, 2010

U.S. Energy Consumption (all sources)

Honeywell



US DOE Buildings Handbook, 2008

Building automation can control 66% of energy in homes and buildings

3 May 24, 2010

Energy Efficiency at Honeywell Automation & Control

Honeywell

- 60% of products & services related to energy
- Large Installed Base
  - 150M+ Homes
  - 10M+ Buildings
  - 5,000+ Industrial Facilities
  - Hundreds of Utilities
  - Over $5B in ESPC savings delivered since '88

Global Leader In Building Controls

4 May 24, 2010

Smart Grid ↔ Home Energy Manager

Honeywell

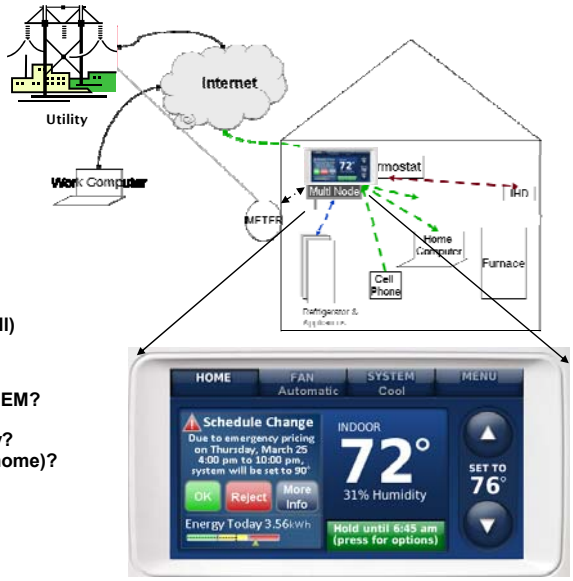
Goal:
- Help utilities reduce peak loads
- Help consumers save $'s

Not all utilities agree with #2

CTQ's:
- Support flexibility in DR programs
- Drive behavior change
- Simple, intuitive, sticky UI

Approach:
- Show meter reading to consumer
- Multiple personas
- Multiple platforms (web/mobile/wall)
- Multiple radios

Questions:
- How to get consumers to look at HEM?
- Can social networking help?
- How to add control w/o complexity?
- Do consumers want more (smart home)?



5

May 24, 2010

How to Effect Behavior Change?

Honeywell

1. Show consumer the meter reading.
   You have used x kWh today/this month/this year.
   What is a kWh?
2. Show history to interpret meter reading.
   You have used y kWh more than yesterday/last month/last year.
   Why? How do I compare to others?
3. Show performance of similar homes in your neighborhood (zip code).
   Out of 100 similar homes in your neighborhood, 87 used less energy.
   How much money am I losing? A few pennies?
4. Show energy performance in $'s.
   Compared to the average, you spend $53 more per month.
   What can I do to save $'s on my monthly energy bill?
5. Make recommendations to save energy $'s.
   Turn up thermostat (in the summer) by a few degrees. SAVE = $20 per month. COST = $0.
   Sign up for a DR program with your utility. SAVE = $25 per month. COST = $0.
   Install thicker insulation in your attic. SAVE = $50 per month. COST = $1000.
   How do you calculate expected savings?
   How do you motivate persistent or lifestyle change?

6

May 24, 2010

Future: Building as Micro-Grid

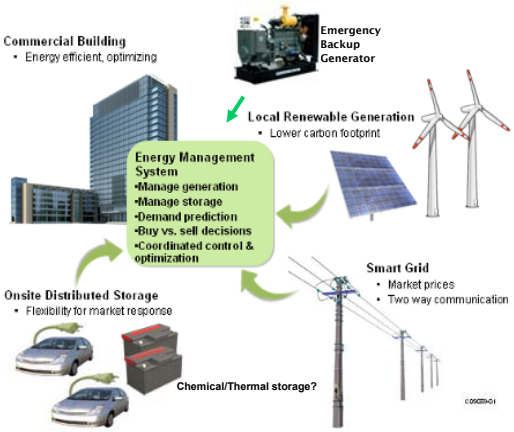
Honeywell

Goal:
- Move toward NZE building
- Improve power reliability

CTQ's:
- Range of DR programs
- Cost-effective storage

Approach:
- Local generation: renewables, turbines
- Storage: batteries, thermal, chemical
- Prediction: demand, supply
- Markets: buy – sell – store decisions
- Participate in EE, DR, islanding

Questions:
- How soon will markets develop?
- Effective storage options
- Renewables output prediction
- PHEV's, part of the equation?
- Lower cost of building model/simulation

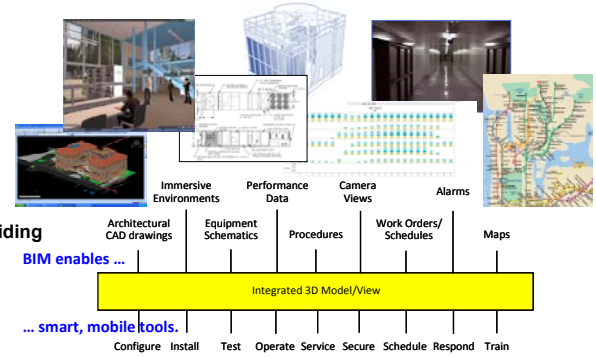


7

May 24, 2010

Future: BIM Enables Mobile Decision Tools

Honeywell



Goal:
- Access BIM for effective decision aiding

CTQ's:
- Simple, intuitive, task-specific
- Common mobile platform, adaptive

Approach:
- Context-aware, knows my task
- Location-aware, knows where equipment is
- Anticipates my information needs
- Access to performance, maintenance history

Questions:
- Distributed sources, limits of BIM coverage
- Security concerns: access based on task
- Business model, 3rd party apps (Apple Store)
- Extend to security, emergency response

8

May 24, 2010

Energy Services for Big Box Retail

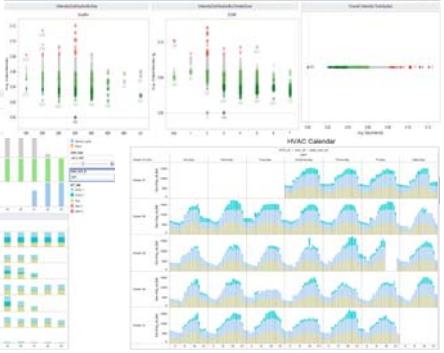
Honeywell

Goal:
- Help Novar analysts do more buildings

CTQ's:
- Quickly ID problem buildings
- Need actionable recommendations
- Auto-generate reports

Approach:
- Office Depot pilot
- Visualize data using Tableau
- Drill down to equipment level
- Look for unusual operation patterns

Questions:
- Sensor coverage
- Heterogeneous buildings?
- What is an appropriate benchmark?



9

May 24, 2010

Summary

Honeywell

Four Case Studies

1. Smart Grid ⇔ Home.
- How do I make the HEM UI sticky?
- How do I motivate persistent behavior change?
- Quick energy models for homes? Need BIM for homes.
- Tie in security, lighting, entertainment?

2. Building as Micro-Grid.
- How soon will carbon market develop?
- Cost-effective generation/storage options
- Prediction for renewables
- Quick energy models for buildings

3. BIM enables Mobile Decision Tools.
- Extend BIM for building operations, security. Why limit BIM to just buildings?
- Data security concerns
- Business model for data access

4. Energy Services for Big Box Retail.
- How many sensors is enough?
- Benchmark for heterogeneous buildings

Miscellaneous.
- Impact of social networking
- Spatial reasoning using BIM
- Extend situation awareness with cell phones

10

May 24, 2010

University of Illinois at Urbana-Champaign

Department of Mechanical Science & Engineering

Estimation & Control Problems in Buildings

Presentation made at the
NSF CMMI Workshop, May 24-25, 2010

Prashant G. Mehta and Sean Meyn
University of Illinois

Acknowledgement: NSF, UTRC

www.mechse.illinois.edu

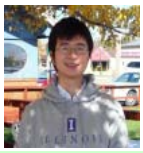
Self-Introduction

2

Professional Experience

2005- Assistant Professor in Mechanical Science and Engineering, Illinois
1996-2005 Research Engineer at United Technologies Research Center, Hartford

Collaboration/Acknowledgement



Kun Deng
Graduate student
MechSe, Illinois

Sean Meyn
Illinois
meyn@illinois.edu

Prabir Barooah
University of Florida
pbarooah@ufl.edu

NSF supported project
CPS: Medium: Collaborative Research: GOALI: Methods for Network-Enabled Embedded Monitoring and Control for High-Performance Buildings

In partnership with: University of Florida (Prabir Barooah), Columbia University (Luca Carloni), United Technologies Research Center (Alberto Speranzon, Satish Narayanan)

Outline of the talk

An overview of (common) problems in buildings

Common mathematical abstractions

Future outlook on common solution strategies

22 Oct, 2008

Cornell University

High Performance Buildings

Objectives: Efficient energy utilization and occupant comfort for normal building operation
Robust response to health and safety threats and events

Energy Efficiency

Energy & mass balances govern steady-state building *energy* performance

"Slow" non-local coupling from air movement system

UTC Power

Carrier

Building

People move--ment & egress

Dynamics - Stochastic

Otis

Security - Fire, smoke, CBR detection & control

Equations for Species transport

Chubb

Communications/ Control network

Local PID loops; global *adhoc*

"Fast" non-local coupling over communication/control network for response to transient events

United Technologies Research Center

High Performance Buildings

Drivers & Enablers

High Performance Buildings **are those that meet or exceed the needs of the occupants at lower life cycle costs and resource utilization than typically realized using conventional methods**

Drivers		*Enablers*
• Multi-threat alarm & response • Safe occupant egress • Contaminant protection	Safe	• Pervasive communication • Occupant tracking technologies • Advances in Chem/Bio sensors
• High indoor air quality • Local occupant control • Interior space flexibility	Healthy	• Control of whole building dynamics • Embedded, network systems • Wireless technologies
• Reduced energy consumption • Combined heat and power • Low maintenance costs	Efficient	• Sensing • Efficient system power utilization • Diagnostic/prognostic capabilities

United Technologies Research Center

Outline of the talk

An overview of (common) problems in buildings

Common mathematical abstractions

Future outlook on common solution strategies

Common Mathematical Abstractions

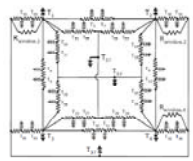
Why Markov processes are useful?

1. Conservation equations for species

$$\frac{\partial c}{\partial t} + \vec{U}(x,y) \bullet \nabla c = D \Delta c$$

2. Thermal models: RC network models of heat flow

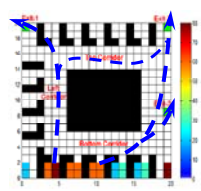
$$\frac{dT}{dt} = AT$$



3. People flow models: Agent movement models

$$Q_i(t+1) = Q_i(t) + \sum_k \Delta_{ki}(t) U_k(t) - U_i(t)$$

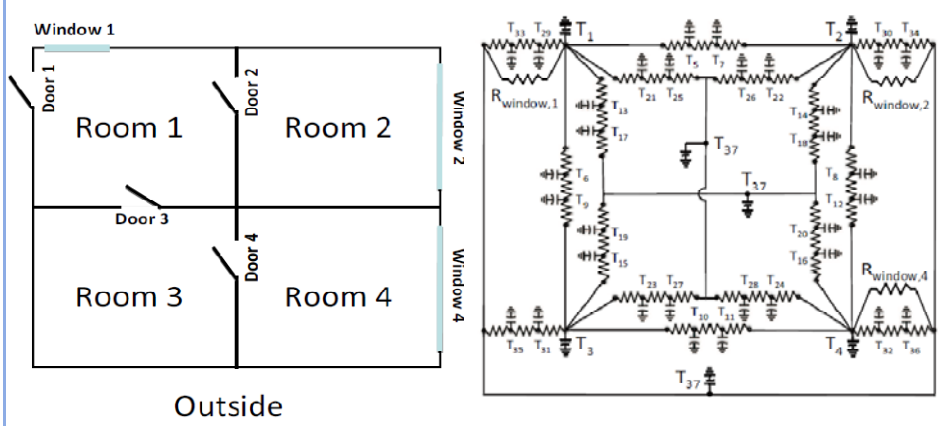
$$\bar{q}_i(t+1) = \bar{q}_i(t) + \sum_k P(k,i) \bar{u}_k(t) - \bar{u}_i(t)$$



Abstracted as Markov processes

The Complexity Issue

Building thermal model and its RC-network representation



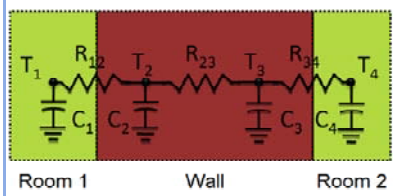
(a) Layout of a 4-room building **(b) RC-network representation**

Kun Deng, P. Barooah, P. G. Mehta, and S. P. Meyn. Building Thermal Model Reduction via Aggregation of States. To appear in 2010 American Control Conference. Baltimore, MD, USA. Jun 2010.

Building thermal model reduction via aggregation of states

A simple two-room example

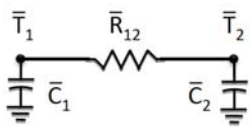
$$\frac{dT}{dt}(t) = AT(t)$$



$$A = \begin{bmatrix} -\frac{1}{C_1R_{12}} & \frac{1}{C_1R_{12}} & 0 & 0 \\ \frac{1}{C_2R_{21}} & -\frac{R_{21}+R_{23}}{C_2R_{21}R_{23}} & \frac{1}{C_2R_{23}} & 0 \\ 0 & \frac{1}{C_3R_{32}} & -\frac{R_{32}+R_{34}}{C_3R_{32}R_{34}} & \frac{1}{C_3R_{34}} \\ 0 & 0 & \frac{1}{C_4R_{43}} & -\frac{1}{C_4R_{43}} \end{bmatrix}$$

(a) Full-order RC-network **(b) Full transition-rate matrix**

$$\frac{d\bar{T}}{dt}(t) = \bar{A}\bar{T}(t)$$

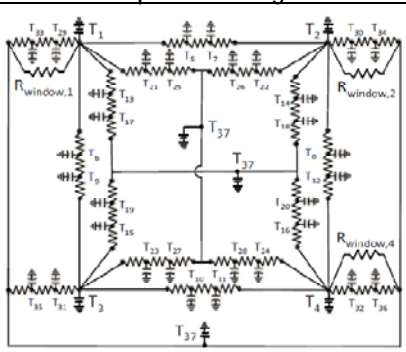


$$\bar{A} = \begin{bmatrix} -\frac{1}{\bar{C}_1\bar{R}_{12}} & \frac{1}{\bar{C}_1\bar{R}_{12}} \\ \frac{1}{\bar{C}_2\bar{R}_{21}} & -\frac{1}{\bar{C}_2\bar{R}_{21}} \end{bmatrix}$$

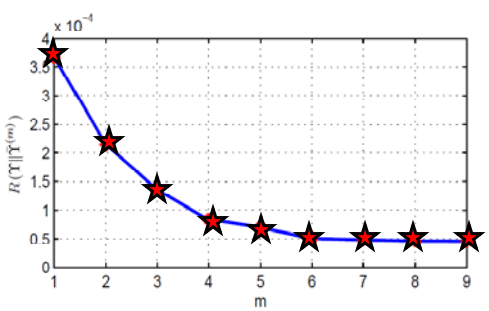
(a) Reduced-order RC-network **(b) Reduced transition-rate matrix**

Building thermal model reduction via aggregation of states

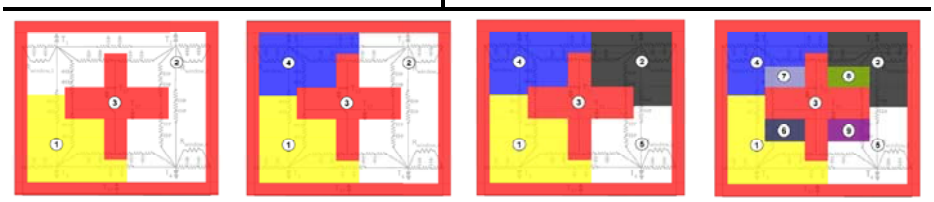
Recursive bi-partition algorithm for aggregation



Original 37-node RC-network



Modeling error for aggregation

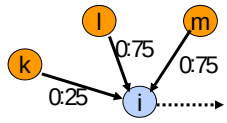


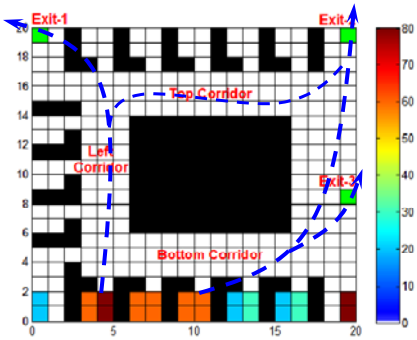
3-partition *4-partition* *5-partition* *9-partition*

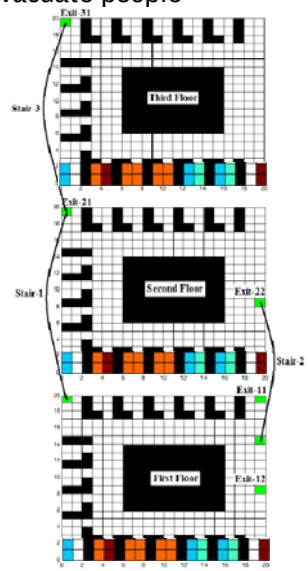
Control of occupancy evolution

Dynamics: Flow of people; Control problem: Evacuate people

Queuing models of agent movement





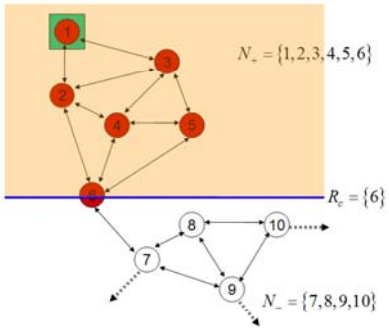


K. Deng, W. Chen, P. G. Mehta, and S. P. Meyn. Resource Pooling for Optimal Evacuation of a Large Building. 47th IEEE Conference on Decision and Control. Cancun, Mexico. Dec 2008.

Control of occupancy evolution

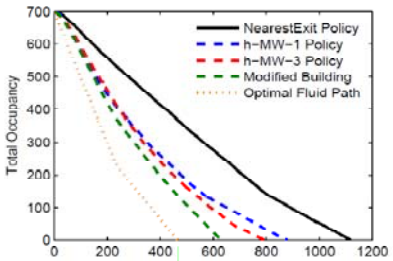
Workload based methods for performance analysis and control design

Workload analysis and relaxation techniques



1. Workload analysis of congested regions
2. Performance bounds on evacuation time
3. Workload-based reduced order modeling
4. Synthesis of distributed control policies
5. Demonstration on simulations

Evacuation policy based on workload relaxation



From simulations

Performance bound

SUN: Receding Horizon Estimation

SUN :Sensor, Utility & Network Structure combined through Constrained Optimization

$$\phi(t) = \begin{pmatrix} x(t) \\ r(t) \end{pmatrix}$$ **Occupancy** **Flow rate**

$$x_i(t+1) - x_i(t) = \sum r_{ji}(t) - \sum r_{il}(t)$$

$$y(t) = C\phi(t) = \begin{bmatrix} C^x & 0 \\ 0 & C^r \end{bmatrix} \phi(t)$$

Optimization:

$$\underset{\phi_0,\ldots,\phi_T}{\arg\min}\left\{ \mathcal{P}_0(\phi_0) + \sum_{t=0}^{T-1}\left(\mathcal{P}_y(\phi(t), y(t)) + \mathcal{P}_d(\phi(t+1), \phi(t)) - \mathcal{U}_{x\,t}(\phi(t)) \right) \right\}$$

Initial belief — Sensor data $y(t)$ — Dynamic constraints — Apriori distribution

- Prior estimation
- Calendar

- Flow sensors
- Sound
- Video…

- Building space usage pattern
- Preferences for walking speed, proximity, path
- Clustering, Lane formation
- Behavior dependence on age, mobility, aggressiveness…

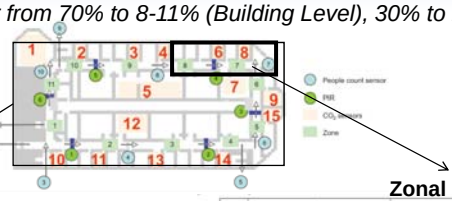
- Calendar data
- Historical record

S. Meyn, A. Surana, Y. Lin, S. M. Oggianu, S. Narayanan, and T. A. Frewen. A Sensor-Utility-Network Method for Estimation of Occupancy Distribution in Buildings. IEEE Conference on Decision and Control, 2009.

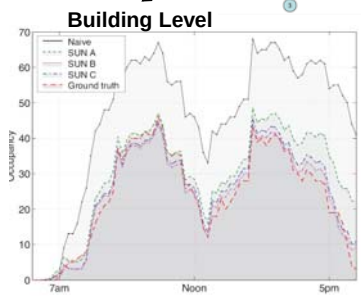
13

Summary : Occupancy Estimation Error

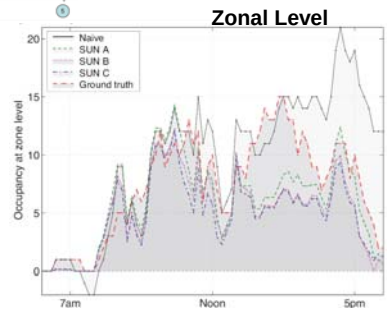
SUN reduces estimation error from 70% to 8-11% (Building Level), 30% to 22% Zonal Level



Building Level



Zonal Level



Ground Truth: Manually by sifting through video data

6pm

$$E = \frac{1}{T_f - T_0} \sum_{t=T_0, x(t)\neq 0}^{T_f} \frac{|x(t) - \hat{x}(t)|}{x(t)}.$$

	Building Level Error	Zonal Level Error
Naive	70%	30%
SUN A	21%	20%
SUN B	8%	21%
SUN C	11%	22%

14

Outline of the talk

An overview of (common) problems in buildings

Common mathematical abstractions

Future outlook on common solution strategies

Basic Research Issues and Needs

16

Common across complex systems and networks

- How to represent and simulate complex systems?
  - Analysis tools for commissioning
  - Performance analysis and off-line optimization
- How to use models for real-time estimation or control?
  - Information management tool
  - Decision support tool
  - Self re-configuring systems
  - Distributed versus centralized implementation

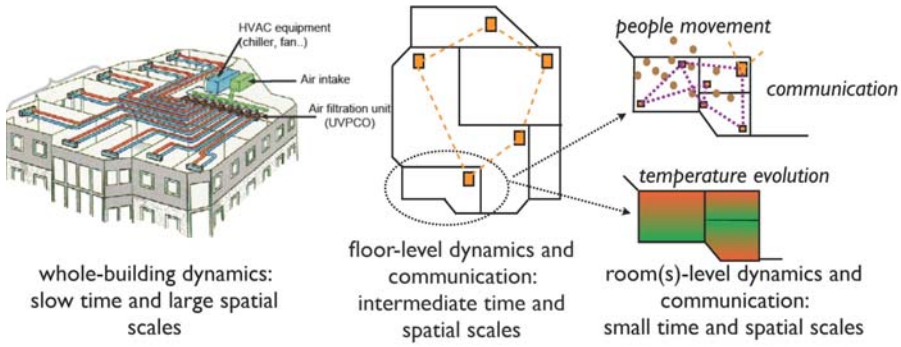
There is no science today that offers the fundamental knowledge necessary to design large, complex networks in such a way that their behaviors can be predicted prior to building them. Given this shortfall, trying to implement network-centric operations capabilities as envisioned by the Department of Defense (DOD) is like trying to design and build a modern combat jet aircraft without resorting to the science of fluid dynamics [taken from NRC report on "Network Science"]

National Research Council Committee on Network Science for Future Army Applications. Network science. National Academies Press, Washington, DC, 2005.

Modeling

17

Issue: Dynamics are coupled and uncertain



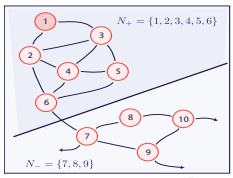
Modeling

18

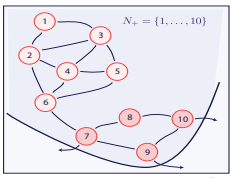
Need: Online model reduction methods that capture the correct scales

Evacuation policy based on workload relaxation

These are network cuts that define the workload



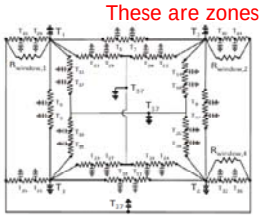
(a) $q(0) = (100, 0, \ldots, 0)^T$



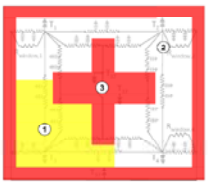
(b) $q(0) = (0, \ldots, 0, 15, 20, 10, 10)^T$

Energy efficiency problems

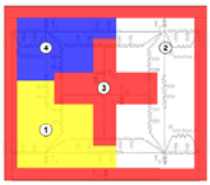
These are zones that capture the slow to intermediate time-scales



Original 37-node RC-network



3-partition



4-partition

Control and Estimation

19

Learning and adaptation are the key

Optimization based framework

Models are complex (high-dimensional) and have large uncertainty

But there exist *low-dimensional features* that are important to estimation and control

It is important to be able to use this a priori information in design of control architectures

Learning based approaches

Use models/reduced order approximations to define appropriate coordinates (basis functions) (e.g., workload vectors)

Adapt these coordinates in an online fashion
(in many applications, this can be done on slow time scale)

Control/estimation algorithms based on approx dynamic programming principles
(e.g., h-maxWeight policies for evacuation, SUN estimator)

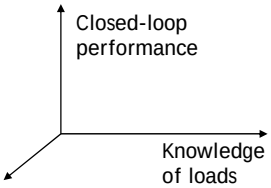
Fundamental limitations and performance trade-offs

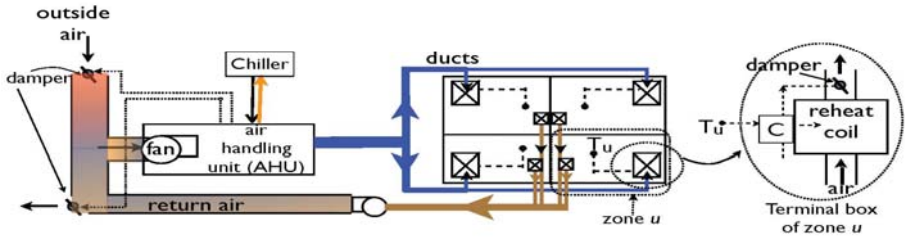
20

Issue: what information is important?

Relative impact of information on closed-loop performance
- Knowledge of real-time thermal loads
- Weather prediction including uncertainty
- Occupancy including distribution of people

❑How much and what information to share
- Distributed versus centralized implementation





Modeling – Smart Grid

21

Issue: Dynamics are <u>coupled</u> and <u>uncertain</u>

Whole-building dynamics, coupled with
- Power grid
- Generation
- Population dynamics … *Smart buildings form key component of future smart grid*

Acknowledgement

22

Kun Deng
Graduate student
MechSe, Illinois

Sean Meyn
Illinois
meyn@illinois.edu

Prabir Barooah
University of Florida
pbarooah@ufl.edu

<u>Papers:</u>

1. Kun Deng, P. G. Mehta, and S. P. Meyn. Optimal Kullback-Leibler Aggregation via the Spectral Theory of Markov Chains. Accepted to appear in IEEE Transactions on Automatic Control.

2. K. Deng, P. G. Mehta, and S. P. Meyn. Aggregation-based Model Reduction of a Hidden Markov Model. Submitted to 49th IEEE Conference on Decision and Control. Atlanta, GA. Dec 2010.

3. Kun Deng, P. Barooah, P. G. Mehta, and S. P. Meyn. Building Thermal Model Reduction via Aggregation of States. To appear in 2010 American Control Conference. Baltimore, MD, USA. Jun 2010.

4. K. Deng, P. G. Mehta, and S. P. Meyn. A Simulation-Based Method for Aggregating Markov Chains. 48th IEEE Conference on Decision and Control. Shanghai, China. Dec 2009. (Winner of 2009 CDC Best Student Paper Award)

5. K. Deng, Y. Sun, P. G. Mehta, and S. P. Meyn. An Information-Theoretic Framework to Aggregate a Markov Chain. American Control Conference. St. Louis, MO, USA. Jun 2009.

6. K. Deng, W. Chen, P. G. Mehta, and S. P. Meyn. Resource Pooling for Optimal Evacuation of a Large Building. 47th IEEE Conference on Decision and Control. Cancun, Mexico. Dec 2008.

7. J. S. Niedbalski, K. Deng, P. G. Mehta, and S. P. Meyn. Model Reduction for Reduced Order Estimation in Traffic Models. American Control Conference. Seattle, WA, USA. Jun 2008.

Building Automation Control Networks

Information flow and control within and between buildings

Steven T. Bushby
Building and Fire Research Laboratory

National Institute of Standards and Technology
NIST

Outline

- Today's Practices, Technologies, and Standards
- Some Emerging Trends and Technologies
- Technical Challenges

Size of the Building Controls Industry

Sector	Value Put In Place $B	% Due to Controls (estimated)	Value of Controls Component $B
Residential	650.5	1	6.5
Commercial / Industrial	286.1*	5	14.3
Manufacturing	31.1*	5	1.6
Public Works	26.0*	5	1.3
		Total	**23.7**

* Estimated VIP of buildings only

Estimates derived from 2005 Census Bureau C30 Report (Value of Construction Put In Place)

Building Construction Process

Design → Bid → Build

- Owner wants a single, general contractor to hold responsible
- Controls subcontractor is several tiers down in the contractual hierarchy
- Cost pressures at each tier result in low margins for controls work
- Minimum first-cost mindset precludes lower-cost investment options based on life-cycle performance
- Commissioning is often not done well and sometimes not at all

Results: Poor quality of installed systems

What happens once the systems are operational?

- Building maintenance staff are often poorly trained
- Contract maintenance based on trouble calls is common
- Overrides or temporary fixes often stay in place preventing the control system from doing its job
- Facility budgets are often seen as a potential place to cut when money is tight

Results: System performance degrades over time

Summary of Industry Characteristics

- Most buildings are "one of a kind"
- Design, bid, build process hampers effective control system design, installation & operation
- First cost mindset reduces innovation
- Most building control systems don't work as intended
- Building systems are poorly maintained
- Limited investment in research (0.5% for construction industry as a whole but probably higher for controls)

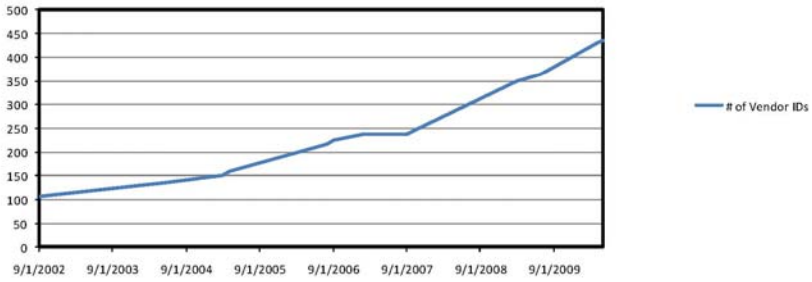
Communication Protocols

Portion of New Installations*

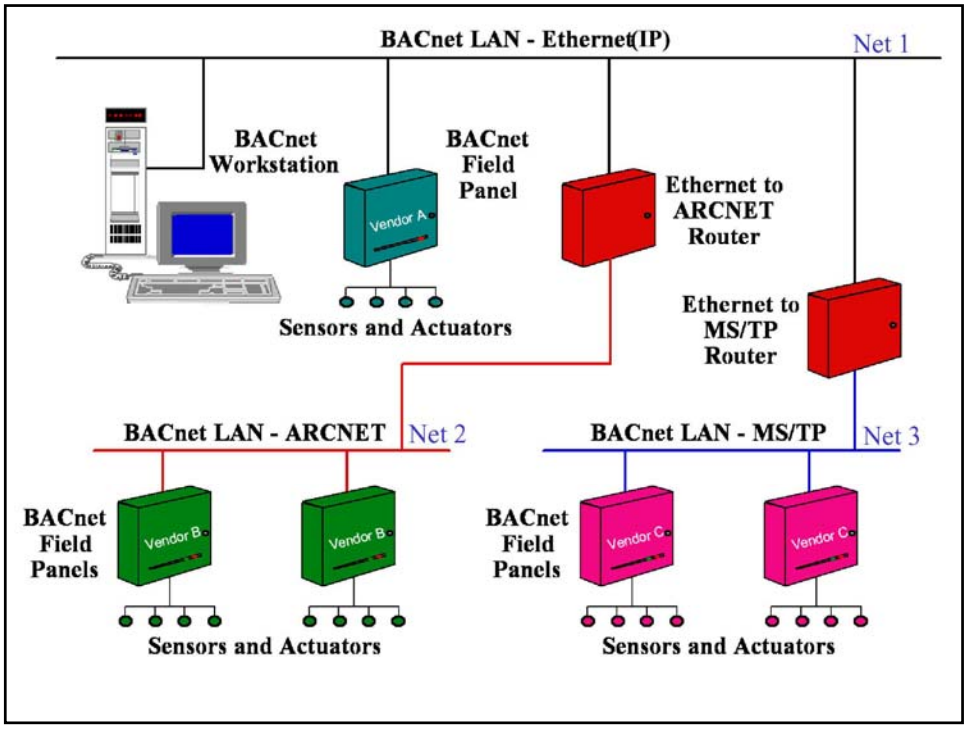
- BACnet (~50% ↑)
- LonTalk (~25%)
- Various proprietary legacy (~25% ↓)

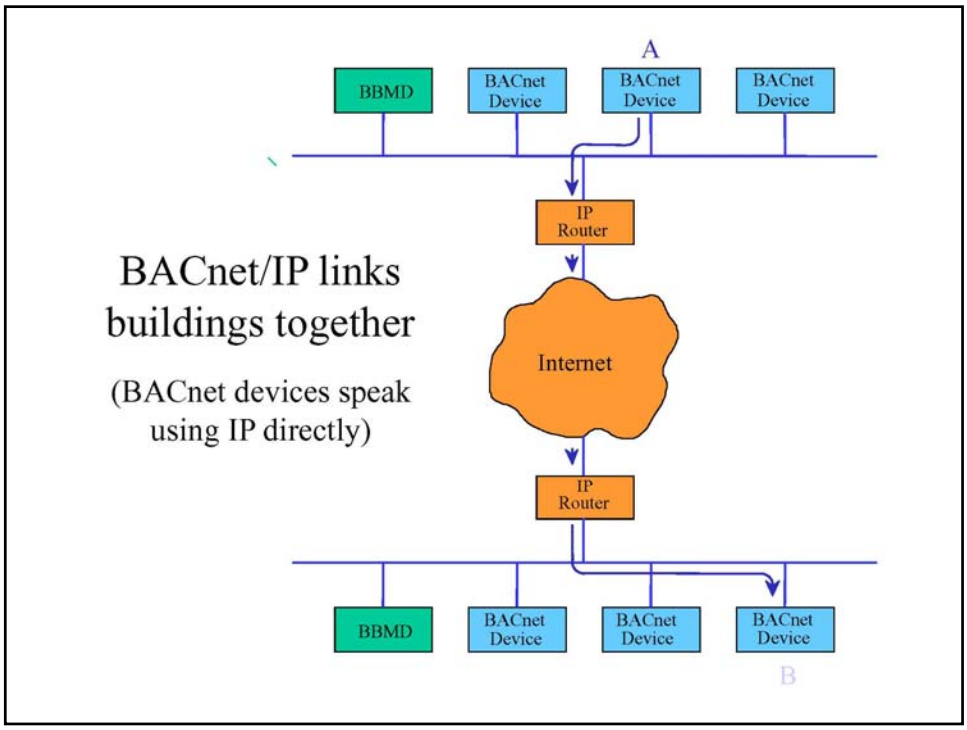
*From a recent North American market survey for CABA– methodology and reliability unknown

BACnet Vendor IDs



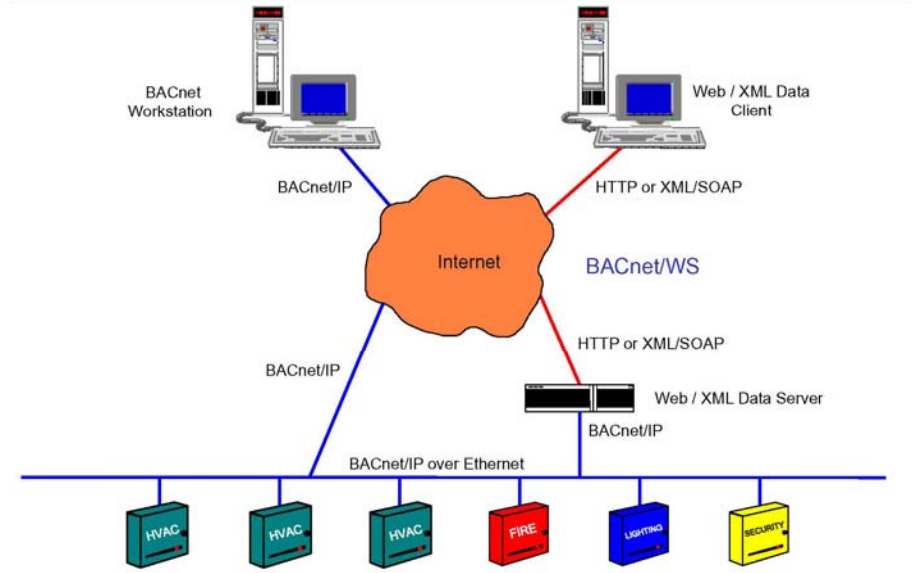
Doubling every 3 -31/2 years


BACnet LAN - Ethernet(IP)
Net 1
BACnet Workstation
BACnet Field Panel
Vendor A
Ethernet to ARCNET Router
Sensors and Actuators
Ethernet to MS/TP Router
BACnet LAN - ARCNET
Net 2
BACnet LAN - MS/TP
Net 3
BACnet Field Panels
Vendor B
Vendor B
BACnet Field Panels
Vendor C
Vendor C
Sensors and Actuators
Sensors and Actuators


A
BBMD
BACnet Device
BACnet Device
BACnet Device
IP Router
BACnet/IP links buildings together
(BACnet devices speak using IP directly)
Internet
IP Router
BBMD
BACnet Device
BACnet Device
BACnet Device
B

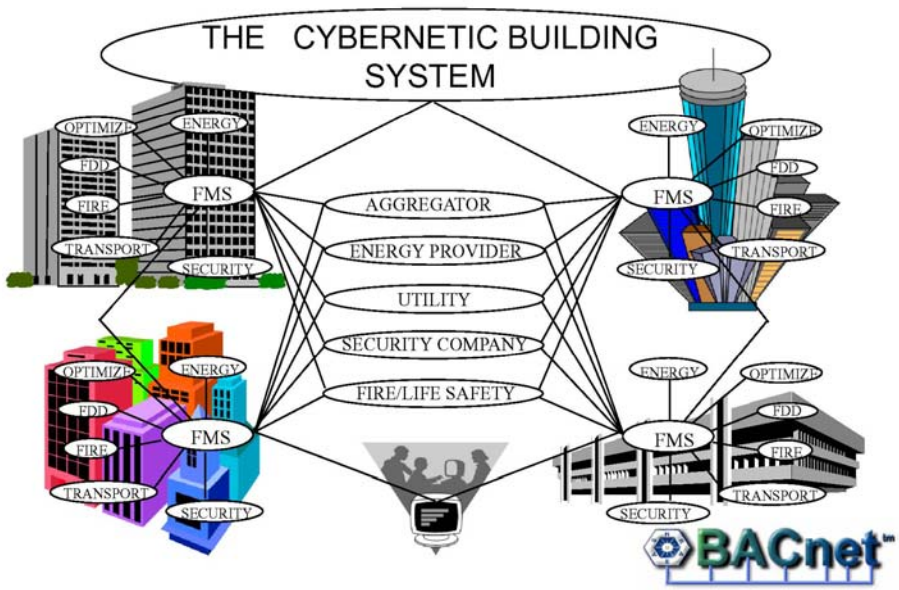
BACnet Web Services

Workstations and Enterprise Integration

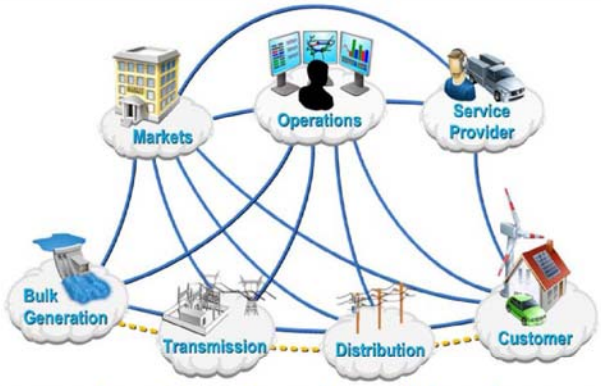


Some Emerging Trends and Technologies

System Integration and Interoperability

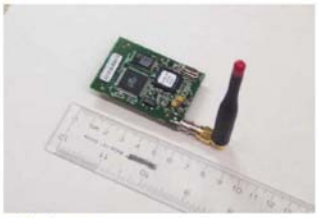


A Smart Grid Requires Smart Buildings



- Response to price signals and load management requests
- Utilities want information about building response (load shedding, load shifting, generation capacity, etc.)

Wireless Sensors



- Advantages
  - Lowers cost of installation
  - Enables addition of sensing in historic buildings
  - Involves less destruction and disruption in existing buildings
  - Enables flexibility in spaces that are frequently reconfigured
  - Allows for placement of sensors in optimal locations instead of "where the wires are"
  - Provide the ability for future expansion

Energy Harvesting Sensors and Actuators

Example - Technology developed by EnOcean

Some Technical Challenges

Configuration, Programming and Commissioning of BAS

- No way to specify design intent and control details in machine readable form
- Configuration/programming prone to human errors
- No automatic system identification
- No plug-and-play
- Functional performance testing is labor intensive

Understanding Limitations and Benefits of Wireless Sensors

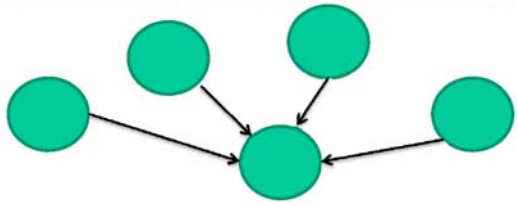
- Signal interference from walls, equipment, other electronic devices
- No performance metrics or standards that can tell how they will work in a particular building
- How to deal with sleep modes?
- Security
- Battery maintenance and power management issues

Increasing Control Complexity

- Growth in system size
- Conflicting control priorities (energy, comfort & productivity, safety, environmental impacts)
- Local renewable energy generation, energy storage, electrical demand management, variable pricing

Data Fusion

- Ubiquitous wireless sensors?
- Aggregated building systems and buildings
- Energy source data – price, quality, environmental impact
- External information such as weather



New Optimization Techniques

- Classical techniques have been shown to be inadequate
- Building systems are discontinuous
- Boundary conditions change significantly
- Heuristic approaches for supervisory control are limited and subject to human error

Embedded Intelligence to Enable Intelligent Building Systems

May 24, 2010

James Braun

School of Mechanical Engineering

Purdue University

CONTENTS

Intelligent Building Systems: Vision → Reality

Need for Low Cost, Embedded Solutions

Automated Diagnostics

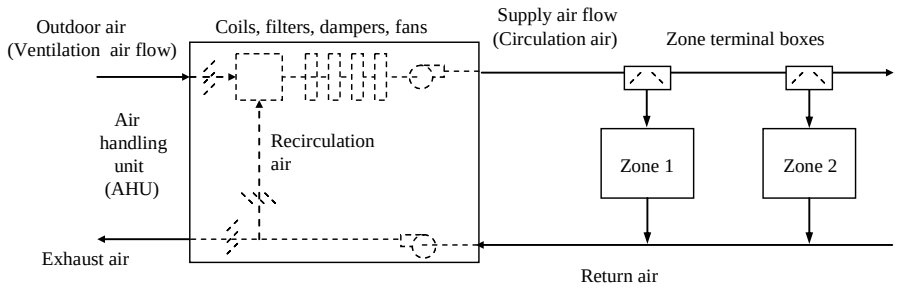
Supervisory Controls

R&D Needs

Introduction

Commercial HVAC System

Typical Air Handling Unit Serving Multiple Zones



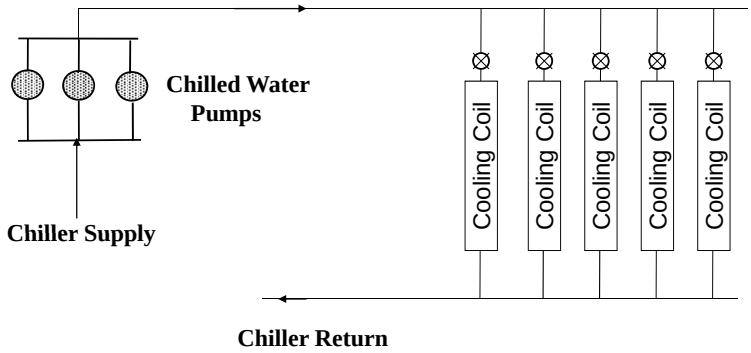
Feedback Control
- zone air dampers
- fan speeds
- cooling/heating coil valves
- ventilation dampers

Supervisory Control
- zone temperature settings
- coil supply air temperatures
- mixed air temperatures

Introduction

Commercial HVAC System

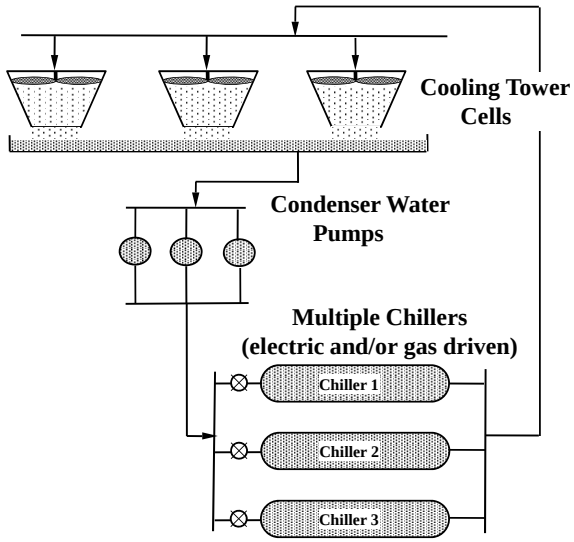
Typical Chilled Water Distribution



Introduction

Commercial HVAC

Typical Conventional Cooling Plant



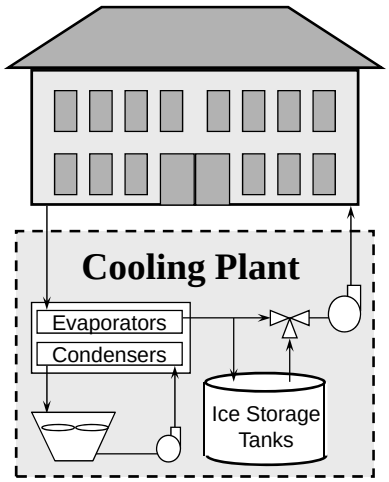
Feedback Control
- compressor loadings
- pump speeds
- tower fan speeds

Supervisory Control
- chiller selection
- chilled water supply temp.
- pump selection
- cond. water supply temp.
- tower selection

Introduction

Commercial HVAC

Typical Ice Storage System



Feedback Control
- compressor loadings
- pump speeds
- tower fan speeds
- storage valve

Supervisory Control
- trajectory of storage charging & discharging rates
- chiller selection
- pump selection
- cond. water supply temp.

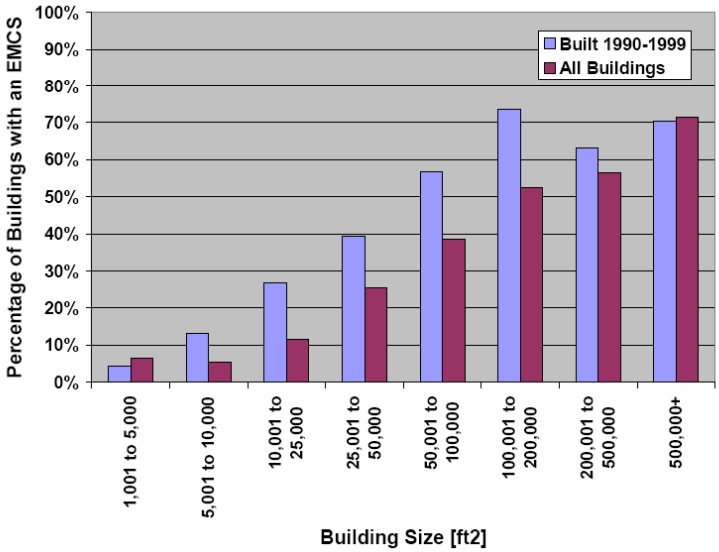
Introduction

Vision for Intelligent Buildings

- Self-diagnose problems, make service recommendations, and identify part requirements/costs
- Coordinate controls to minimize operating costs using building-specific information and weather and utility information
- Access to information using a variety of devices (LCD, PDA, PC, TV, Phone, FAX) across a variety of pathways (LAN, WEB, wireless)
- Integration of energy management, security, and safety functions

Introduction

But where are we?



Introduction

Barriers to More Intelligent Buildings

- Relatively high cost of engineering and maintaining advanced control features
  - Buildings are not mass produced → practically all buildings are different and require unique engineering solutions
  - Building systems continually change throughout their lifetime
  - Smaller buildings with packaged HVAC typically don't have operational personal
  - Large built-up HVAC systems may incorporate thousands of control variables and monitored points at different system levels
    - Zone Level - thermostats and terminal boxes
    - Air Handling Unit Level – control valves for cooling and heating coils, ventilation control, fan control
    - Plant Level – multiple chiller sequencing and loading with multiple energy sources, pump controls, cooling tower controls, thermal storage control

Introduction

Barriers to More Intelligent Buildings

- Benefits are often difficult to quantify and sell
  - Energy and maintenance costs are much smaller than "people" costs for commercial applications
  - Difficult to quantify impact of improved indoor environments on productivity
  - Building owners lack the skills and tools to understand impacts of poor controls or maintenance on energy costs
  - Utility cost incentives for intelligent operations vary widely between locations, class of service, and over time
    - Fixed price energy
    - Time-of-use energy and demand charges
    - Real-time-pricing of electricity
    - Critical peak pricing of electricity

Introduction

Improving Cost-Benefit Ratio

- Standard communication protocols (e.g.,BACNET)
  - greater competition leading to lower costs and better features
- Decreasing installation costs
  - Less wiring → distributed architectures, use of existing enterprise networks (e.g., Ethernet), wireless communications
  - More tools for configuring and commissioning components
- Growing incentives
  - higher energy costs, utility programs
- Consolidation of Large Controls, Equipment, Service, and Facility Operations Companies
  - moving towards an environment of hardware as a commodity and operations/service as the big money maker

CONTENTS

Introduction

Need for Low Cost, Embedded Solutions

Automated Diagnostics

Supervisory Controls

R&D Needs

Need for Low Cost Solutions
Comparisons with Other Applications

Increasing Benefits

Benefits	Applications
Safety	Nuclear Power Air Craft
Reduced Product Costs	Chemical Process Plants Manufacturing Plants
Lower End-Use Operating Costs (Maintenance & Energy)	Automotive HVAC

Allowable Costs

Need for Low Cost Solutions
Measurement Costs vs. Benefits

Increasing Costs

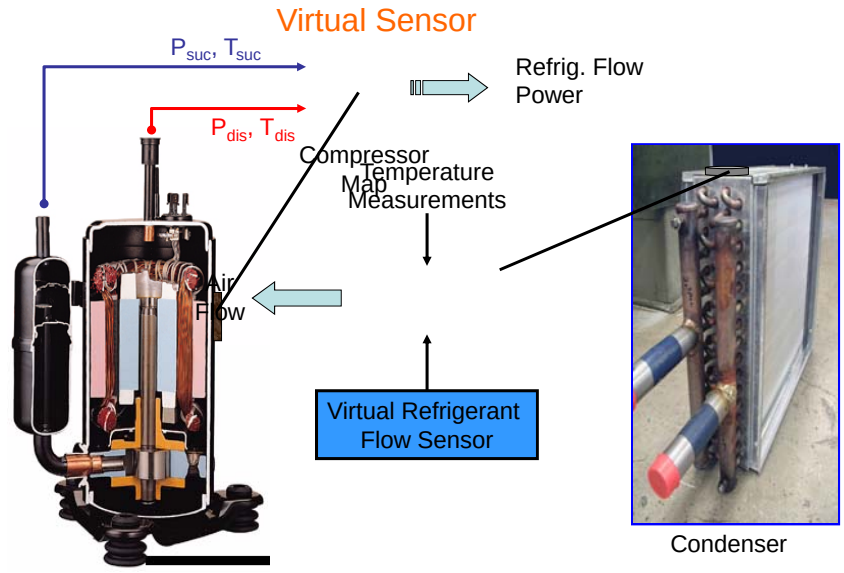
Measurements	Application
Vibration	Predict Mechanical Failures
Energy Use	Performance Impact Evaluation
Pressures/Temperatures	Detect and Diagnose Thermal System Problems

Increasing Benefits

Need for Low Cost Solutions
Keys to Widespread Intelligent Buildings

- Embed intelligence in individual building system components → turn intelligent features into commodities not programming projects
- Make it dirt cheap to install and configure intelligent building system components
- Allow access to information from any intelligent component using a variety of readily available devices (computer, PDA, phone,..) and interfaces (e.g., web browsers)

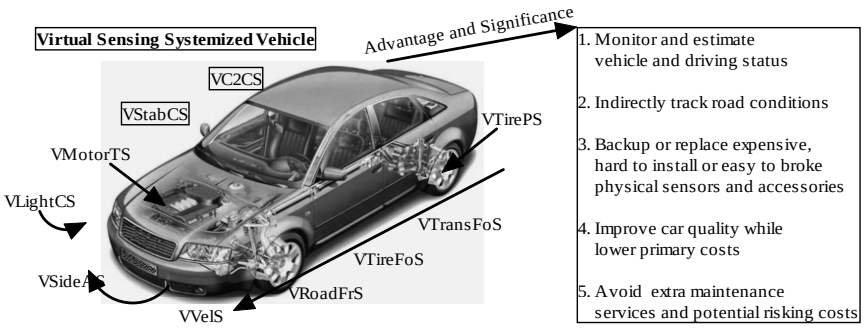
Need for Low Cost Solutions
Example of Embedded Intelligence



Need for Low Cost Solutions
Virtual Sensing

- Use models and low-cost measurements to obtain high value indirect measurements
  - e.g., refrigerant flow and power from pressure and temperature measurements and compressor model
- Particularly useful to enable cost effective performance monitoring and automated diagnostics

Need for Low Cost Solutions
Virtual Sensing for Automobiles



VTirePS-Virtual vehicle tire-air pressure sensor
VTireFoS-Virtual vehicle tire-road forces sensor
VTransFoS-Virtual vehicle transversal forces sensor
VRoadFrS-Virtual vehicle road friction sensor
VSideAS-Virtual vehicle sideslip angle sensor
VVelS-Virtual vehicle velocity sensor
VC2CS-Virtual vehicle car-2-car communication sensor
VMotorTS-Virtual motor combustion timing sensor
VLightCS-Virtual vehicle enhanced lighting preview control sensor
VStabCS-Virtual vehicle stability control sensor

CONTENTS

Introduction

Need for Low Cost, Embedded Solutions

Automated Diagnostics

Supervisory Controls

R&D Needs

Automated Diagnostics

Vision for Automated Diagnostics

Automated Diagnostics
Overview of Previous R&D

- Vapor Compression Equipment (chillers, packaged AC & heat pumps)
  - Identification of most common and expensive faults using detailed service records
  - Vibration signature analysis for mechanical (e.g., bearing) faults
  - Variety of approaches using thermodynamic measurements for faults that degrade performance (fouling, refrigerant leakage, compressor degradations, etc.)
  - Algorithms for optimal scheduling of heat exchanger maintenance and filter replacement
  - Some limited assessments of the economic benefits of automated diagnostics

Automated Diagnostics
Overview of Previous R&D

- Air Handling Units
  - Identification of most common faults
  - Rule-based approaches for economizer diagnostics
  - Rule-based and model-based approaches for fan, heat exchanger faults
- Whole Building Fault Analysis
  - Inverse modeling approaches for identifying changes in overall energy usage
  - Rule-based approach for resolving conflicts between fault reports from equipment-specific diagnostic outputs

Automated Diagnostics
Products for Packaged AC Equipment

- Diagnostic Hand Tools
  - A number of competitive products
  - Costs spread over many systems
  - Generic rule-based approaches
- On-Line Performance Monitors
  - Software integrated into energy management or add-on system
- Embedded Diagnostics
  - Products under development
  - Requires low cost sensors (e.g., temperatures only)
  - Can employ equipment-specific information

Automated Diagnostics
Diagnostic Approaches for Packaged AC

- Thermodynamic Impact
  - associate specific faults with changes in thermodynamic (e.g., temperature) measurements
  - requires models for “expectations” under normal conditions
  - does not handle multiple-simultaneous faults
- Decoupling Features
  - identify quantities that uniquely depend on individual faults (e.g., air flow)
  - can handle multiple-simultaneous faults
  - utilize “virtual sensors” to eliminate expensive measurement requirements (e.g., flow rates)

Automated Diagnostics

Compressor Decoupling Example

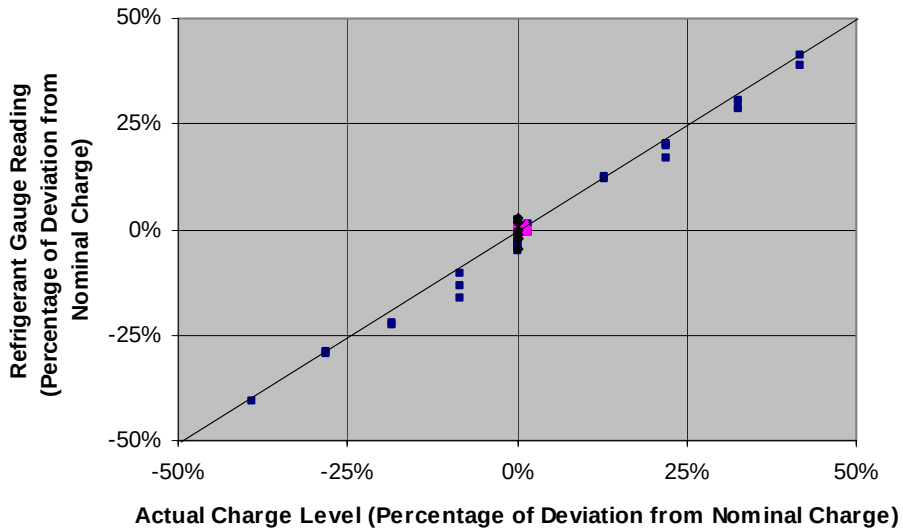
Compressor Valve Problems → Reduced Flow → Higher Specific Work → Higher Discharge Temperature

Automated Diagnostics

Virtual Refrigerant Charge Gauge Demo

Automated Diagnostics

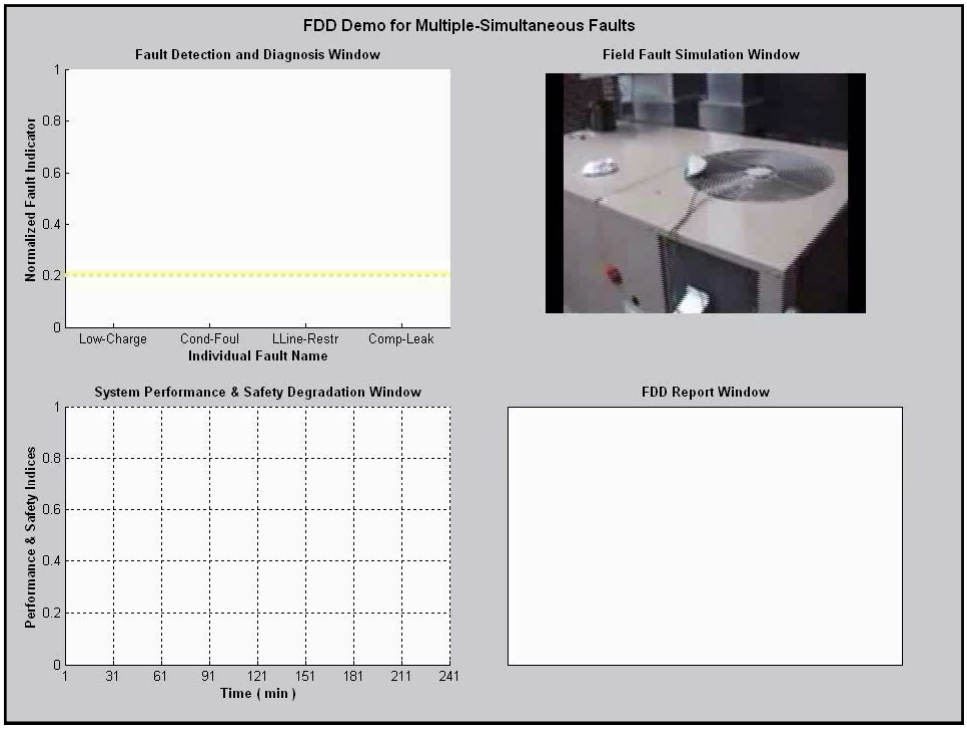
Virtual Refrigerant Charge Sensor



Automated Diagnostics

Example Virtual Sensors

Virtual Sensor Output	Measurement & Model
Refrigerant Mass	Four surface mounted temperatures & correlation
Refrigerant Pressure	Surface temperature in two-phase section & refrigerant properties
Refrigerant Flow Rate	Two pressures, one temperature & correlation (compressor map, valve model)
Compressor Power	Two pressures, one temperature & correlation (compressor map)
Air Flow	Differential pressure, one temperature & correlation (fan characteristic)



CONTENTS

Introduction

Need for Low Cost, Embedded Solutions

Automated Diagnostics

Supervisory Controls

R&D Needs

Supervisory Control

Previous R&D

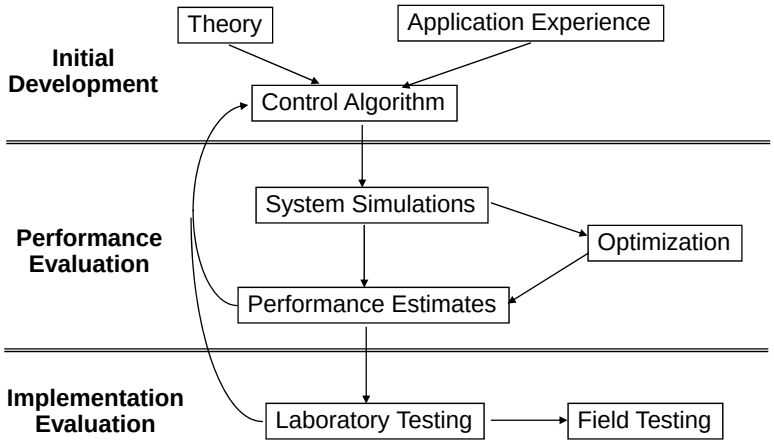
- Savings Potential through Optimal Supervisory Control
  - Optimization of cooling plant setpoints and modes of operation (<10% savings potential)
  - Optimal charge and discharge control of ice storage systems (<10% for conventional utility rates, >20% for real-time pricing)
  - Optimal control of building thermostat setpoints to take advantage of building thermal mass (up to 40% cost savings)
- Real-Time Optimal Control
  - Demonstrations for cooling plant, ice storage, and building thermal mass control
- Embedded (Near-Optimal) Control Strategies
  - Developed for a number of different applications

Supervisory Control

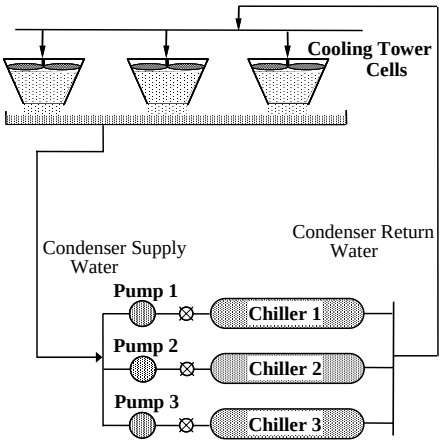
Embedded Control Strategies

- Many near-optimal control algorithms developed for commercial buildings
  - Return from night setup/setback
  - Cooling tower sequencing and fan control
  - Chiller sequencing and setpoint adjustments
  - VAV fan static pressure reset
  - Night ventilation precooling
  - Ice and chilled water storage control
  - Hybrid gas/electric plants
  - Demand-limiting with building thermal mass

Supervisory Control
Control Strategy Development



Supervisory Control
Hybrid Cooling Plant Example



- Combination of gas and electric chillers (absorption, engine-driven, centrifugal)
- Primary advantage is reduced electrical demand charges
- Gas chillers typically have greater maintenance and energy costs
- Optimal chiller control switches between electric and gas chillers depending on utility rates
- Optimal cooling tower control varies with chiller choices and load

Intelligent Control

Hybrid Plant - Benchmark Optimization

Monthly Optimization: Minimize utility and maintenance cost (J_p) with respect to a peak plant power limit ($P_{pl,limit,p}$)

electric demand rate ($/kW)

$$J_p = \sum_{k=1}^{N} J_k^* + DR_p P_{pl,\lim it,p}$$

Minimum hourly energy/maintenance cost

Hourly Optimization: At each hour, minimize

$$J_k = f(tower\ control, chiller\ selection, chiller\ loading, energy\ rates)$$

Subject to constraints on control variables and equipment limits and the daily demand constraint.

Intelligent Control

Hybrid Plant – Decoupled Strategies

- Near-optimal strategies for hourly energy optimization with demand constraints
  - Energy cost optimal cooling tower fan settings based on design parameters, energy rates, and chiller loadings
  - Chiller sequencing and loading strategies for minimum energy cost subject to a demand constraint
- Monthly heuristic strategy for setting demand target
  - Reset target each billing period using simple heuristic

Intelligent Control

Hybrid Plant – Simplified Tower Control

Tower Air Flow for Two-Speed Fans (from optimization theory)

Rated tower approach

Rated tower range

Chiller part-load ratio

Cost of energy input for chiller

Rated chiller energy input

$$\gamma_{twr} = \left\{ \frac{1}{2}\left(a_{twr,rated} + r_{twr,rated}\right) \sum_{i=1}^{N_{ch}} \left(PLR_{ch,i}\, f_{twr,rated,i}\right) \sum_{i=1}^{N_{ch}} \left(PLR_{ch,i} S_{ch,rated,i} \frac{ER_i E_{ch,rated,i}}{ER_e P_{twr,rated}} \right) \right\}^{1/3}$$

Relative tower air flow

Rated power of tower fans

Cost of electricity

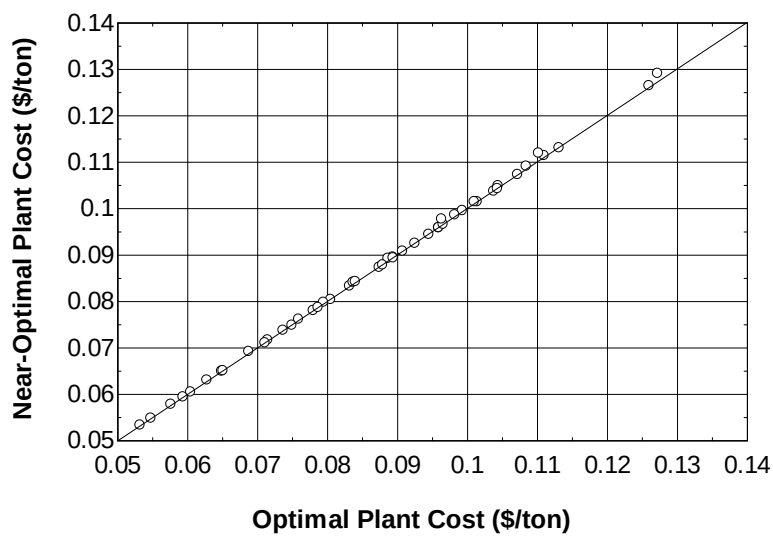
Ratio of chiller heat rejection to total tower heat rejection at rating condition

Sensitivity of chiller input energy to condenser temperature

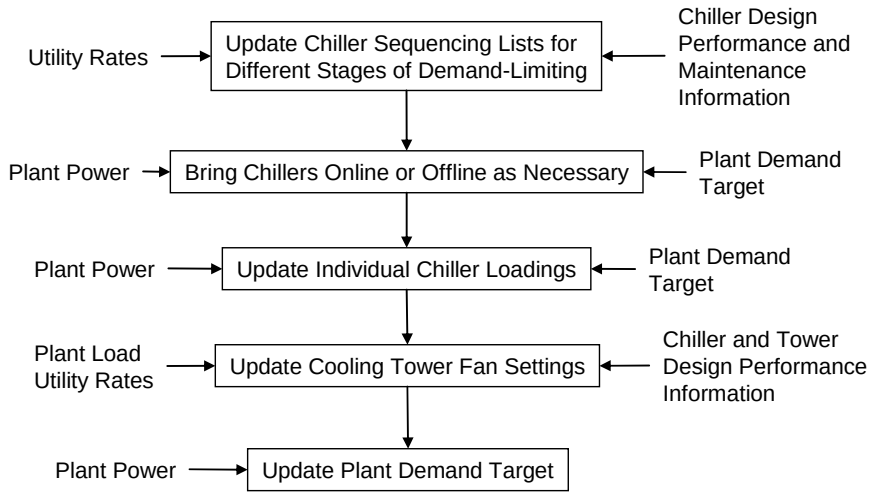
- Relative air flow converted to specific fan speed settings using optimal sequencing rules

Supervisory Control

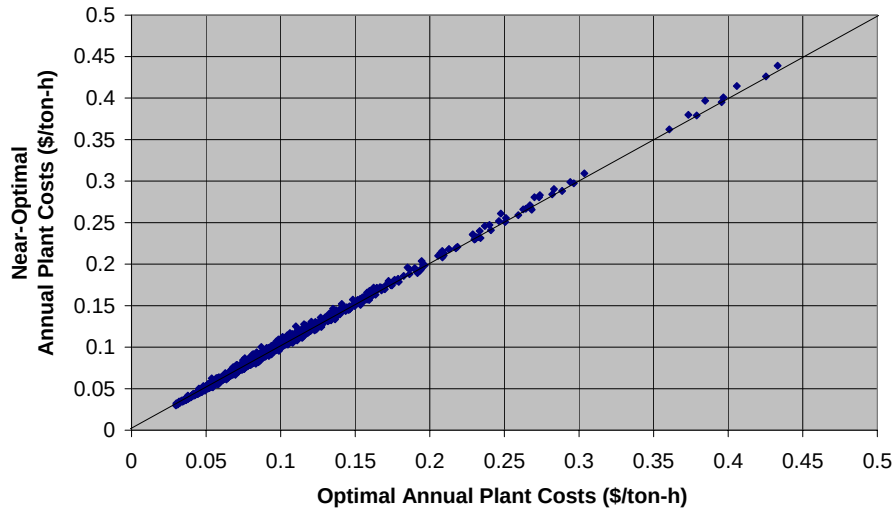
Hybrid Plant – Tower Strategy Performance



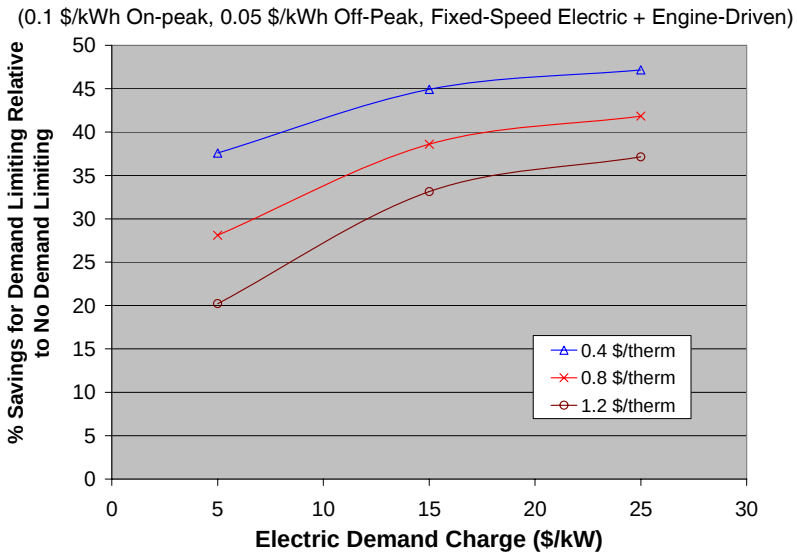
Supervisory Control
Hybrid Plant – Overall Strategy



Supervisory Control
Hybrid Plant – Overall Strategy Performance

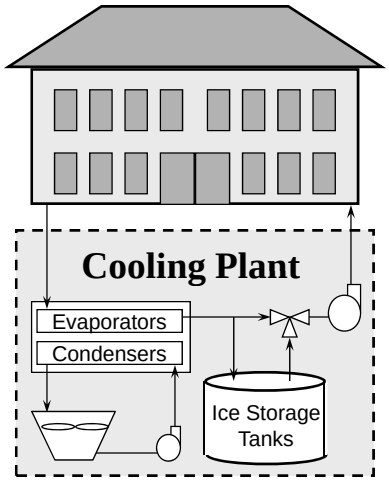


Supervisory Control
Hybrid Plant – Example Savings



Supervisory Control
Ice Storage Control with Real-Time Pricing

Typical Ice Storage System



Benchmark Optimization

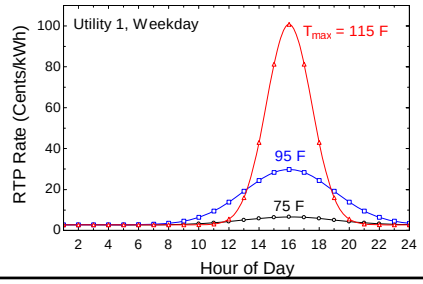
Minimize

$$J = \sum_{k=1}^{N} R_k P_k \Delta t$$

Cooling plant power (kW)

Hourly energy cost ($/kWh)

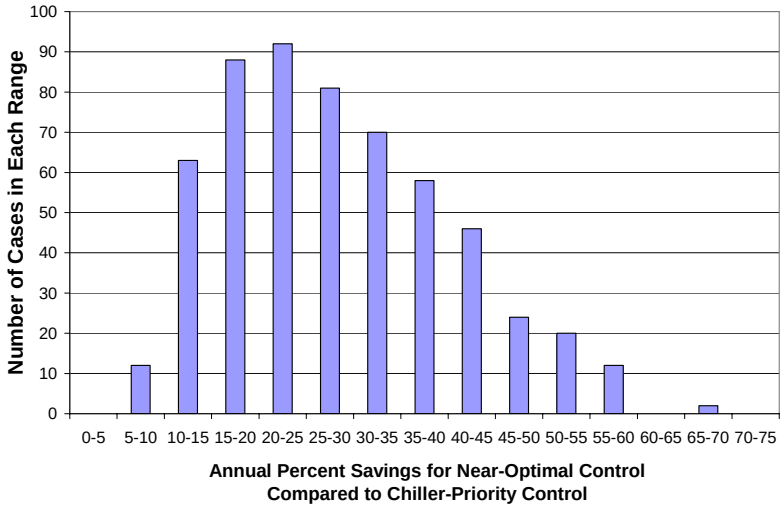
with respect to hourly charging and discharge rates of storage and subject to constraints



Supervisory Control

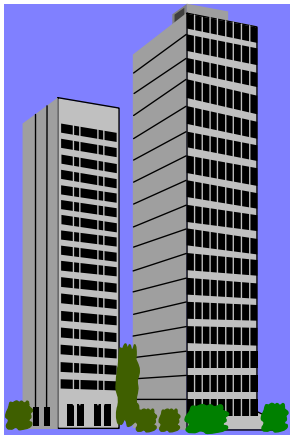
Ice Storage – RTP Controller Savings

Savings Compared to Chiller-Priority Control (576 different systems)



Supervisory Control

Building Thermal Mass Control



Benchmark Optimization

Minimize

$$J = \sum_{k=1}^{N} \left\{ EC_k P_k \Delta t \right\} + Max_{1 \le k \le N} \left\{ DC_k P_k \right\}$$

w.r.t. hourly zone thermostat settings (T_z) and subject to comfort and other constraints

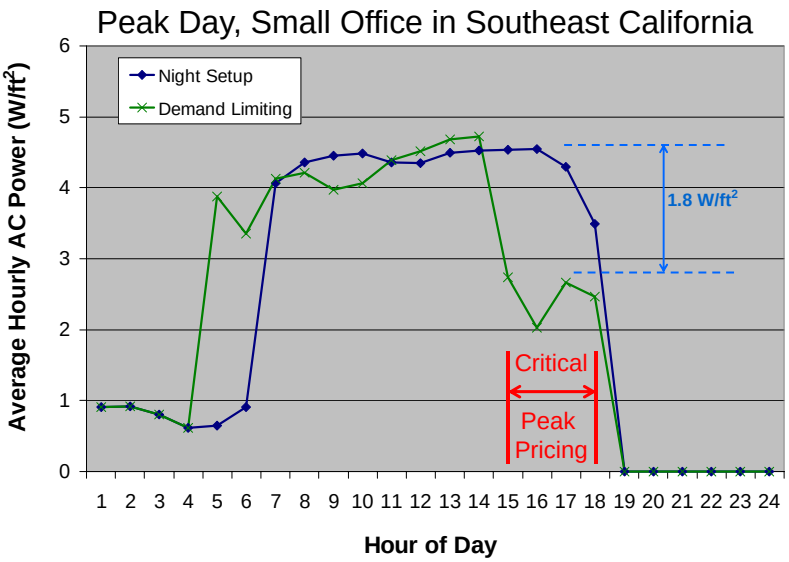
$$T_{z,\min,k} \le T_{z,k} \le T_{z,\max,k} \qquad \vec{x}_k = f(\vec{x}_{k-1}, T_{z,k}, k)$$

$$\vec{x}_{\min} \le \vec{x}_k \le \vec{x}_{\max}$$

J = monthly utility cost
P = building electrical power (kW)
EC = cost per unit of electrical energy ($/kWh)
DC = cost per monthly peak power demand ($/kW)
x_k = vector of states for condition of energy storage

Supervisory Control

Example Demand-Limiting Results



CONTENTS

Introduction

Need for Low Cost, Embedded Solutions

Automated Diagnostics

Supervisory Controls

R&D Needs

R&D Needs

Embedded Solutions

- Embedding performance characteristics, virtual sensors, supervisory control algorithms, and diagnostics at the factory within individual components and equipment could reduce costs and takes advantage of manufacturer specific information
  - enables plug-and-play capability to reduce implementation costs
  - prospects are improved by consolidation of controls, equipment, and service companies
- Necessary to develop appropriate communication protocols, configuration approaches, and conflict resolution schemes to enable diagnostics and optimal supervisory control at the system level

R&D Needs

Embedded Automated Diagnostics

- Identify appropriate decoupling features for the components, equipment, and subsystems found in buildings
- Develop appropriate virtual sensors for decoupling features and other needed monitoring information
- Develop appropriate communication protocols, configuration approaches, and conflict resolution schemes to enable system-level performance monitoring & automated diagnostics using embedded intelligence (i.e., local virtual sensor & diagnostic information)
- Demonstrate fully distributed diagnostic systems that employ embedded intelligence

R&D Needs

Embedded Supervisory Control

- Develop embedded near-optimal control algorithms for building thermal mass (e.g., smart thermostat)
- Develop appropriate communication protocols, configuration approaches, and conflict resolution schemes to enable system-level optimal control using embedded intelligence (i.e., cost-control sensitivities)
- Demonstrate fully distributed optimal control systems that employ embedded intelligence

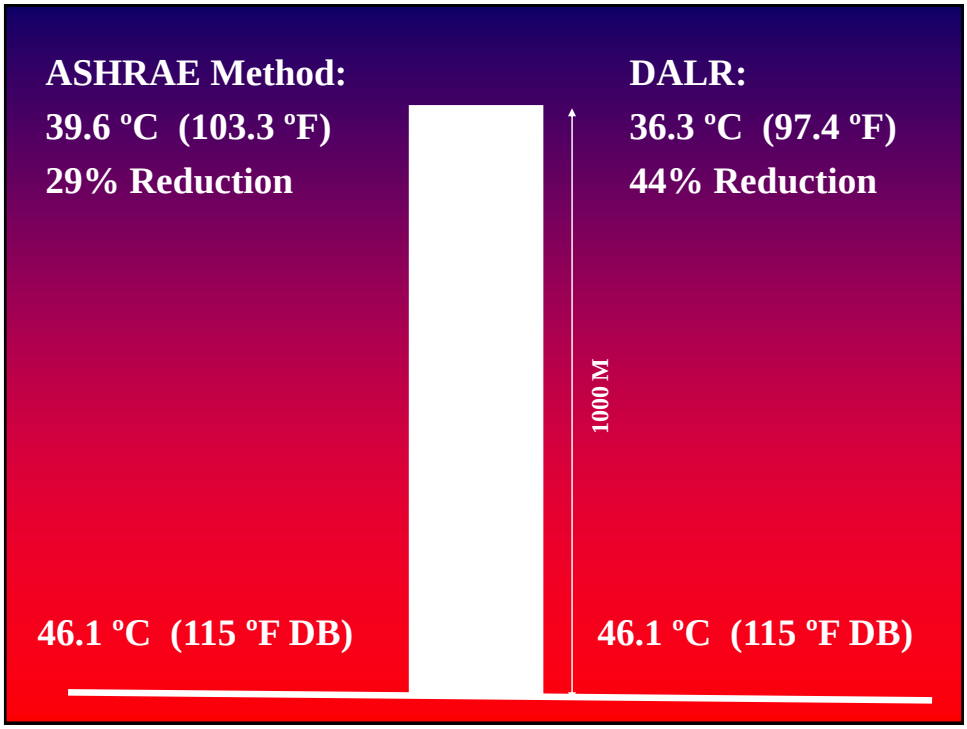
The End

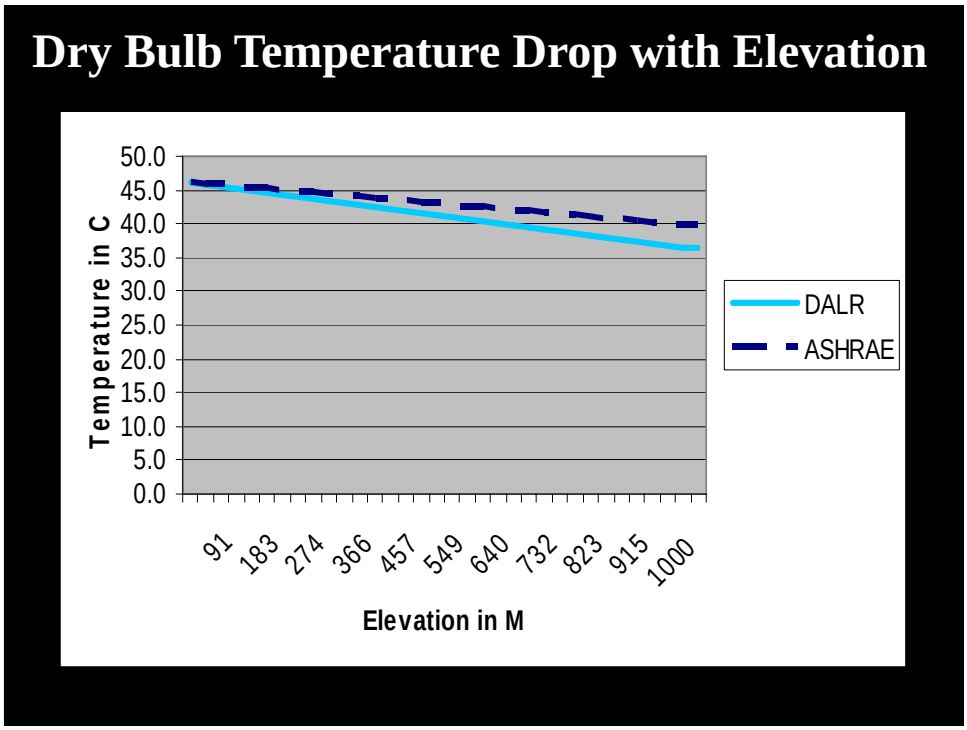
Questions?

Questions?

Burj Dubai Natural Environment and Building Control

Dry Bulb Temperature


ASHRAE Method:
39.6 ºC (103.3 ºF)
29% Reduction
DALR:
36.3 ºC (97.4 ºF)
44% Reduction
1000 M
46.1 ºC (115 ºF DB)
46.1 ºC (115 ºF DB)


Dry Bulb Temperature Drop with Elevation
Temperature in C
50.0
45.0
40.0
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
91
183
274
366
457
549
640
732
823
915
1000
Elevation in M
DALR
ASHRAE

Temperature Inversion

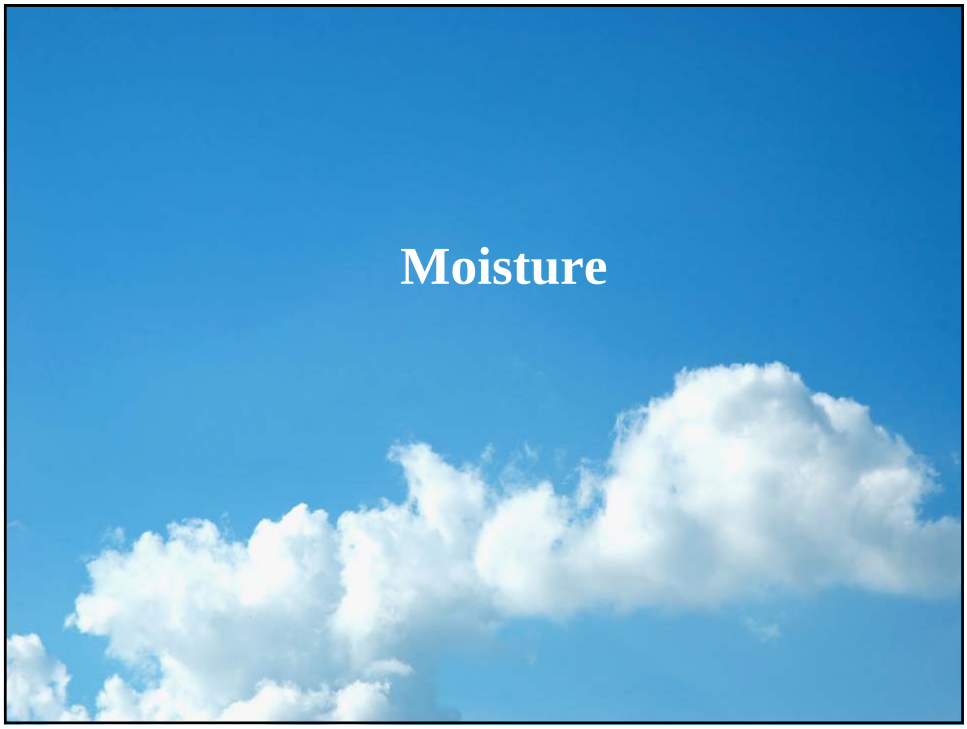
Cooling Predominant Environment:

Benefit:

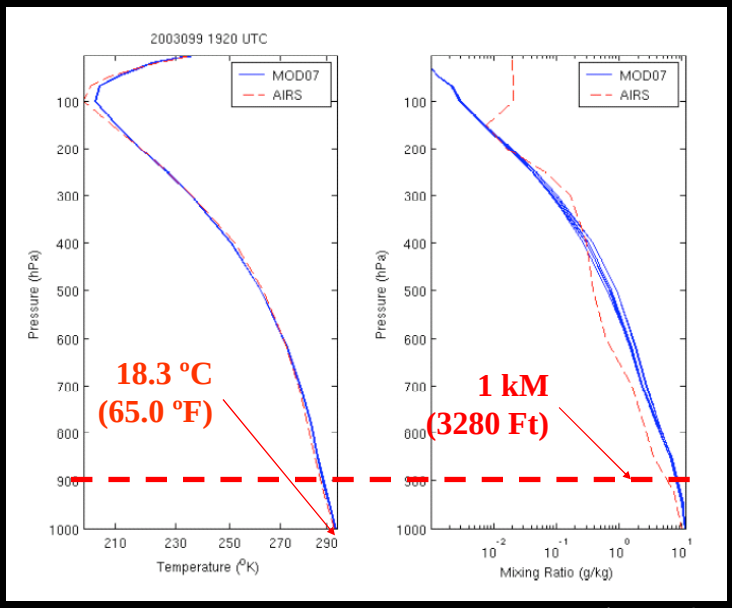
- Conduction Heat Gain Decrease
- Infiltration (Sensible) Decrease
- Increase in Radiant Comfort

Total Summer Cooling
Load Savings
in the Hottest Hour:

- About 10%



Moisture Can Decrease with Elevation



University of Wisconsin-Madison

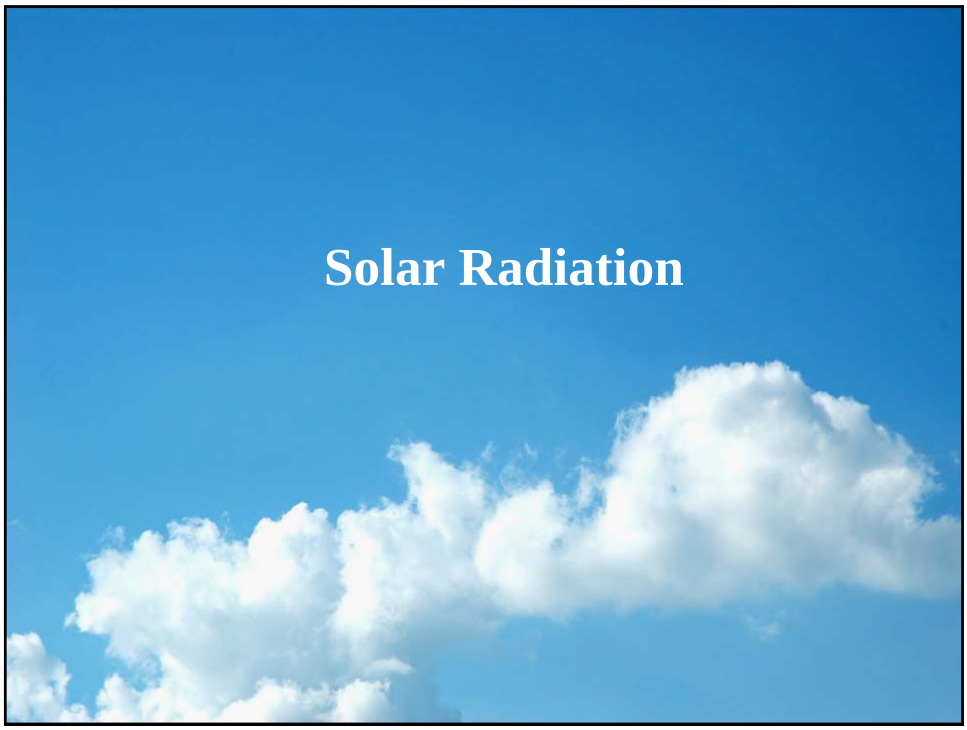
Cooling Predominant Environment:

Benefit:

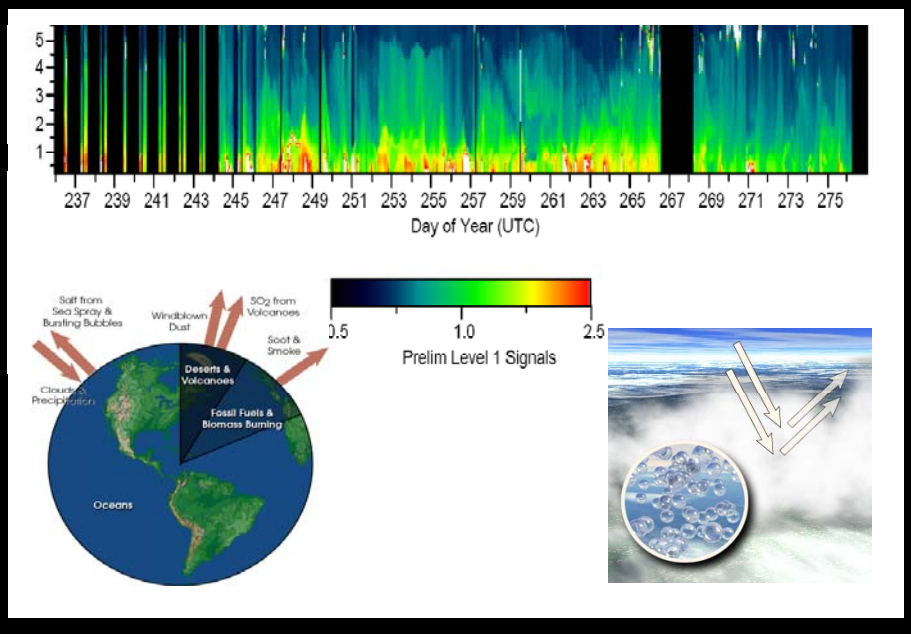
- Reduction in Ventilation Latent
- Infiltration (Latent) Decrease
- Less Moisture Related Issues

Total Cooling Load Savings in the hottest hour:

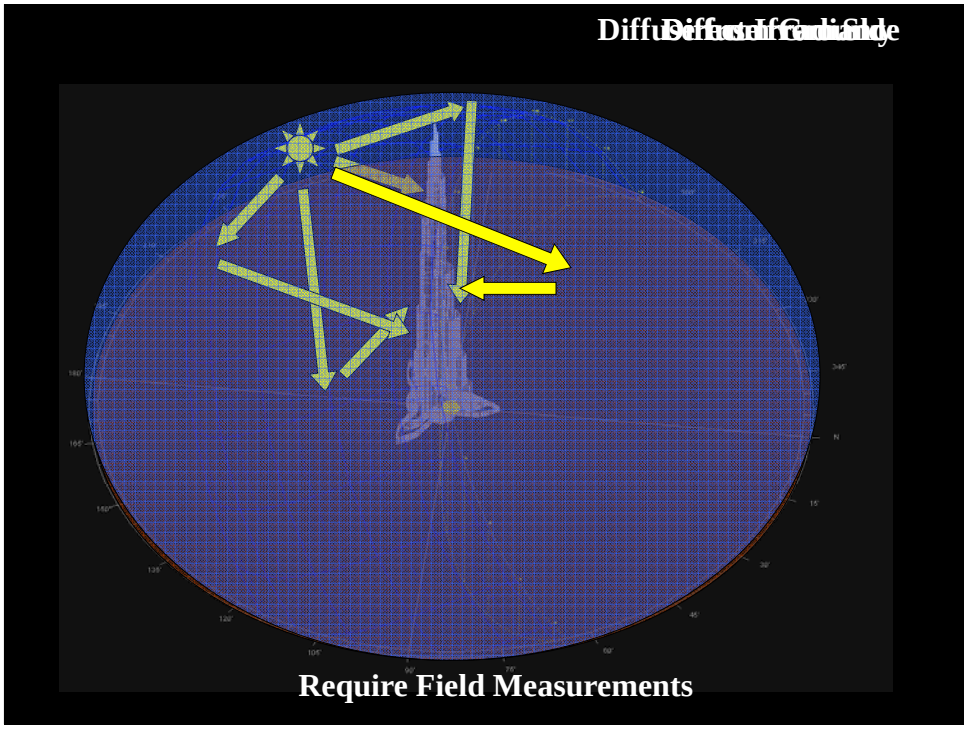
- About 0-4%



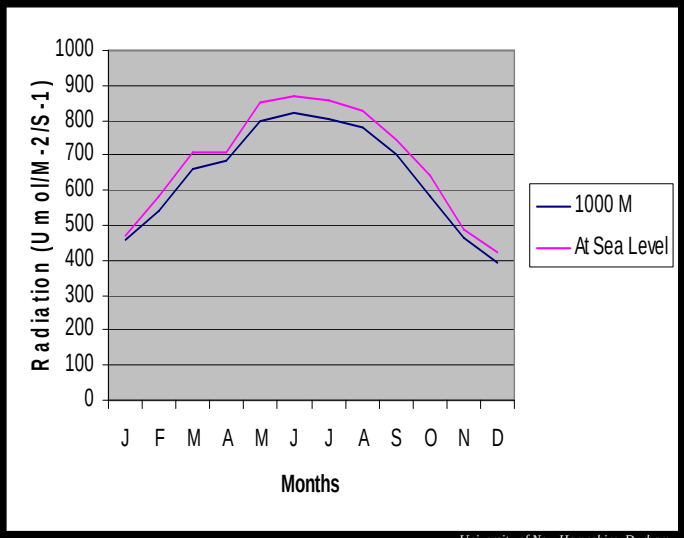
Aerosols



Aerosols Impact the Amount of Available Radiation

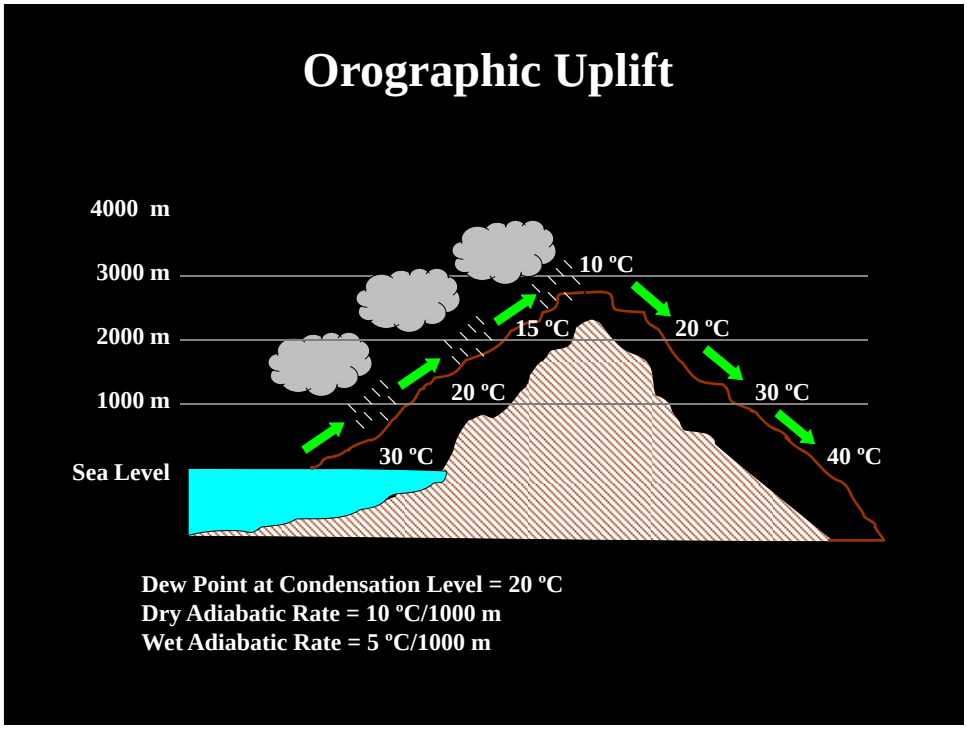


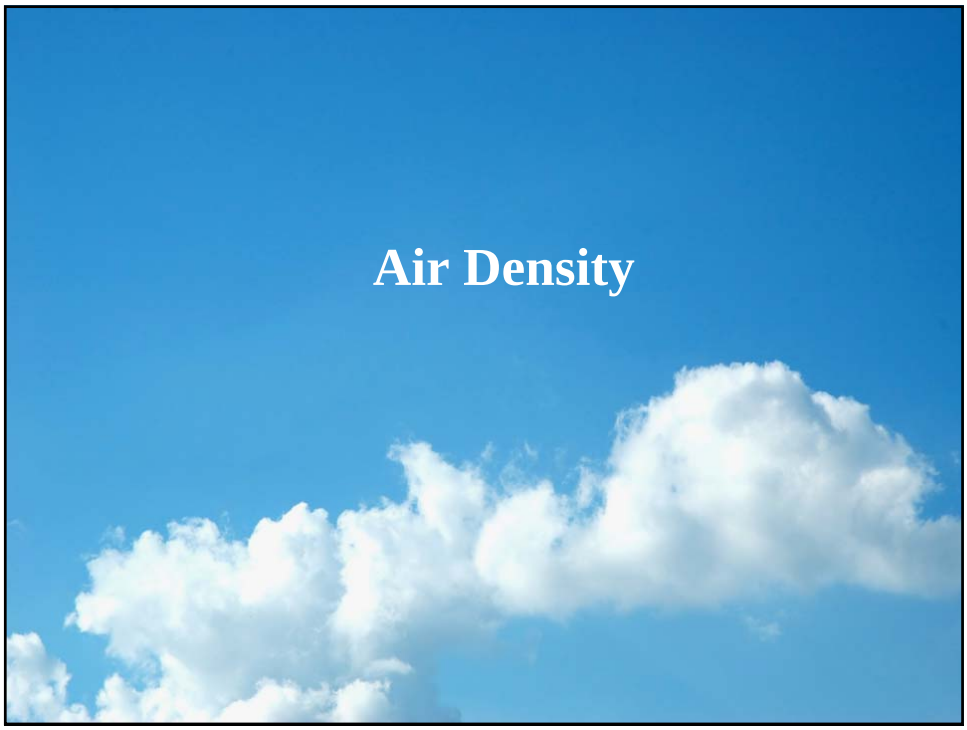
Solar Radiation and *CITY* Elevation



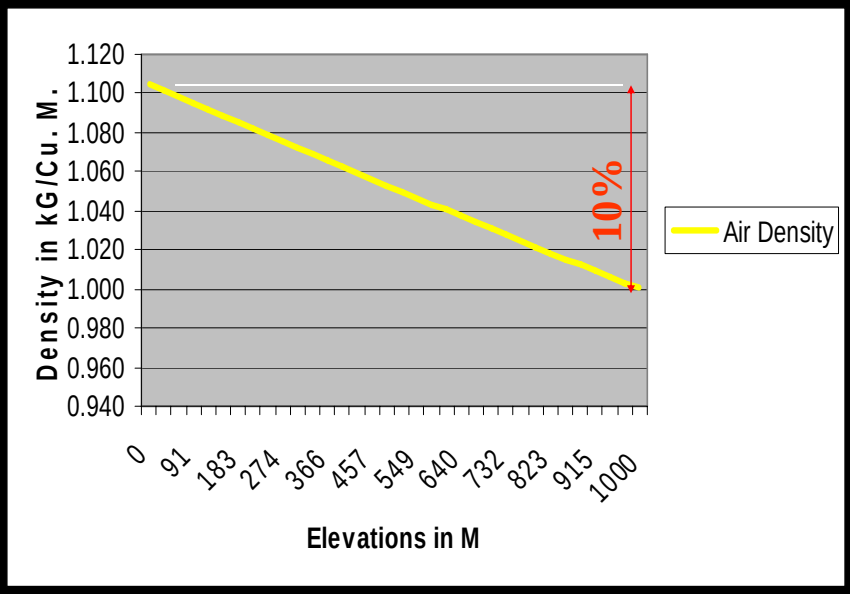
Months	Differences (Sea level vs. 1000 M)
J	3.0%
F	8.0%
M	6.2%
A	3.6%
M	6.1%
J	5.3%
J	6.4%
A	5.5%
S	5.9%
O	9.5%
N	5.6%
D	7.4%

University of New Hampshire, Durham


Orographic Uplift
4000 m
3000 m
2000 m
1000 m
Sea Level
10 ºC
15 ºC
20 ºC
30 ºC
20 ºC
30 ºC
40 ºC
Dew Point at Condensation Level = 20 ºC
Dry Adiabatic Rate = 10 ºC/1000 m
Wet Adiabatic Rate = 5 ºC/1000 m


Air Density

Air Density Drop with Elevation



Air Density: ASHRAE Standard 62.1-2007 "Ventilation for Acceptable Indoor Air Quality" : Ventilation rates ***may*** be adjusted for actual density but such adjustment is ***not*** required for compliance with this standard."

= 17 CFM at the top of the building 100%

=15 CFM at the bottom of the building 88%, 12% savings

=13.8 CFM at Standard Atmosphere, 81%, 19% savings

**** Does the Amount of Oxygen Matter?***

Cooling Predominant Environment:

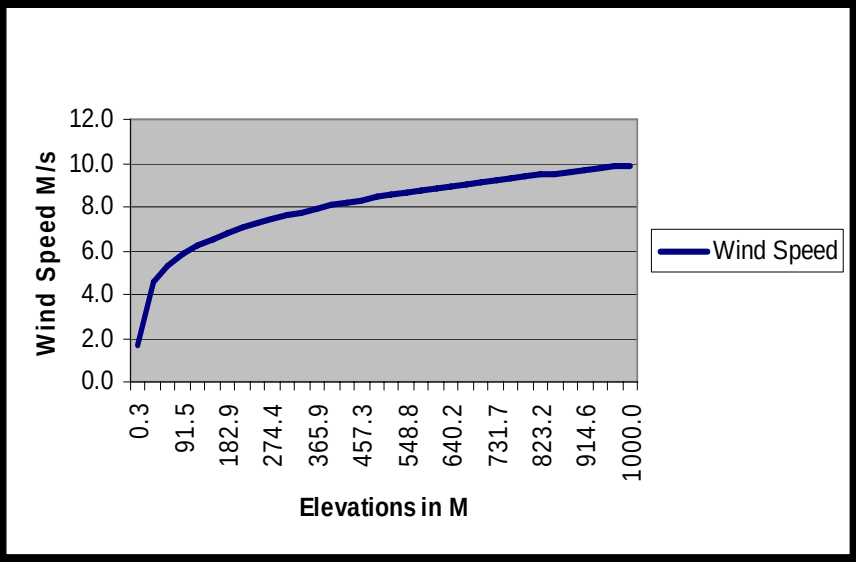
Benefit:

- Reduction in Ventilation Load
- Reduction in Ventilation Fan Energy

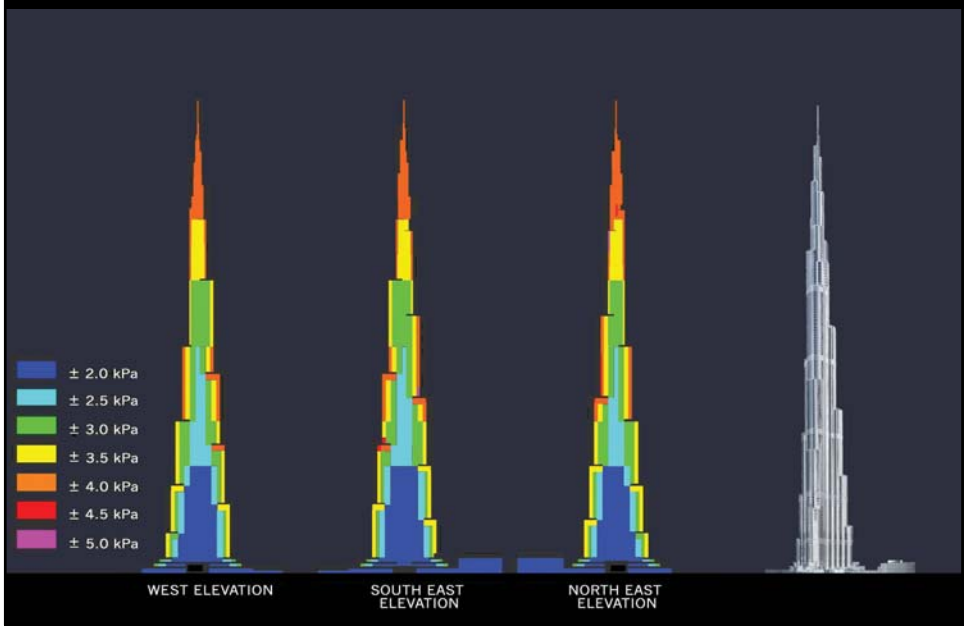
Total Cooling Load Savings in the hottest hour:

- About 3-4%

Wind Speed Increases with Elevation



Wind Speed Varies with Location on Building

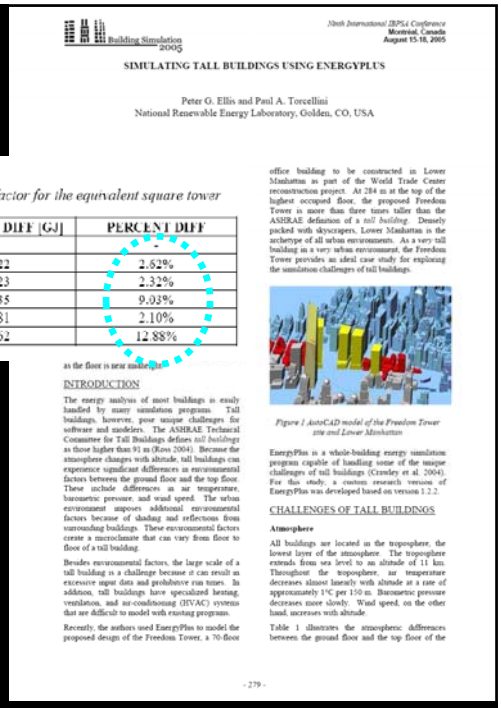


Cooling Predominant Environment Loads:

Temperature:	10%
Moisture:	0%
Air Density:	4%
Wind:	-1%
Solar:	?
Total:	13%

- Also Increase in Comfort Because of Mean Radian Temperature
- Less Harsh Environment
- Utilitzing Wind as Fan Power

Freedom Tower Study



Building Simulation 2005

Ninth International IBPSA Conference
Montréal, Canada
August 15-18, 2005

SIMULATING TALL BUILDINGS USING ENERGYPLUS

Peter G. Ellis and Paul A. Torcellini
National Renewable Energy Laboratory, Golden, CO, USA

Table 2
Impact on annual cooling and heating energy by environmental factor for the equivalent square tower

ENV. FACTOR	TOTAL ENERGY [GJ]	ABSOLUTE DIFF [GJ]	PERCENT DIFF
None	65,711	-	-
Temperature	63,989	1,722	2.62%
Wind	64,188	1,523	2.32%
Shading	59,776	5,935	9.03%
Reflection	64,331	1,381	2.10%
Combined	57,249	8,462	12.88%

office building to be constructed in Lower Manhattan as part of the World Trade Center reconstruction project. At 284 m at the top of the highest occupied floor, the proposed Freedom Tower is more than three times taller than the ASHRAE definition of a *tall building*. Densely packed with skyscrapers, Lower Manhattan is the archetype of all urban environments. As a very tall building in a very urban environment, the Freedom Tower provides an ideal case study for exploring the simulation challenges of tall buildings.

as the floor is near midheight.

INTRODUCTION

The energy analysis of most buildings is easily handled by many simulation programs. Tall buildings, however, pose unique challenges for software and modelers. The ASHRAE Technical Committee for Tall Buildings defines *tall buildings* as those higher than 91 m (Ross 2004). Because the atmosphere changes with altitude, tall buildings can experience significant differences in environmental factors between the ground floor and the top floor. These include differences in air temperature, barometric pressure, and wind speed. The urban environment imposes additional environmental factors because of shading and reflections from surrounding buildings. These environmental factors create a microclimate that can vary from floor to floor of a tall building.

Besides environmental factors, the large scale of a tall building is a challenge because it can result in excessive input data and prohibitive run times. In addition, tall buildings have specialized heating, ventilation, and air-conditioning (HVAC) systems that are difficult to model with existing programs.

Recently, the authors used EnergyPlus to model the proposed design of the Freedom Tower, a 70-floor

Figure 1 AutoCAD model of the Freedom Tower site and Lower Manhattan

EnergyPlus is a whole-building energy simulation program capable of handling some of the unique challenges of tall buildings (Crawley et al. 2004). For this study, a custom research version of EnergyPlus was developed based on version 1.2.2.

CHALLENGES OF TALL BUILDINGS

Atmosphere

All buildings are located in the troposphere, the lowest layer of the atmosphere. The troposphere extends from sea level to an altitude of 11 km. Throughout the troposphere, air temperature decreases almost linearly with altitude at a rate of approximately 1°C per 150 m. Barometric pressure decreases more slowly. Wind speed, on the other hand, increases with altitude.

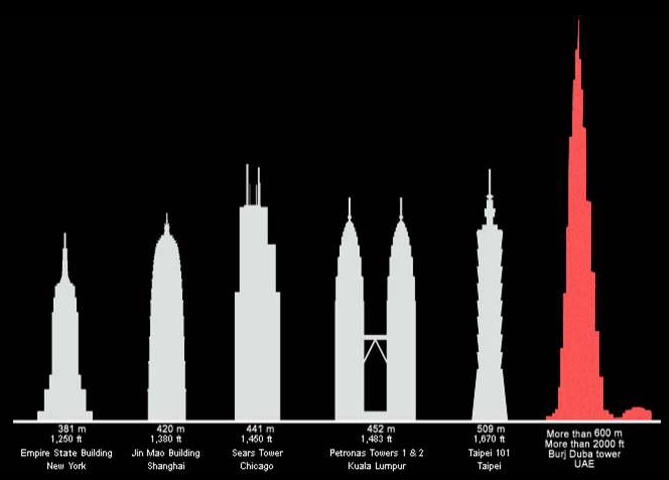
Table 1 illustrates the atmospheric differences between the ground floor and the top floor of the

- 279 -

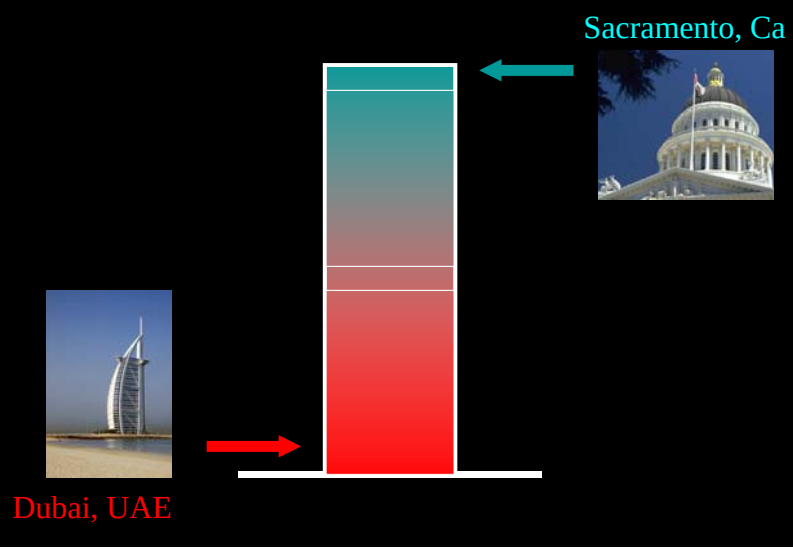
What is Missing?
- Air Density Changes
- Humidity Changes
- Stack Effect

Credit: National Renewable Energy Laboratory

How are the new Super Tall buildings different than what came before?



Should a Design Reflect it's Environment? If so, which One?



Burj Dubai: Magnitude of Difference

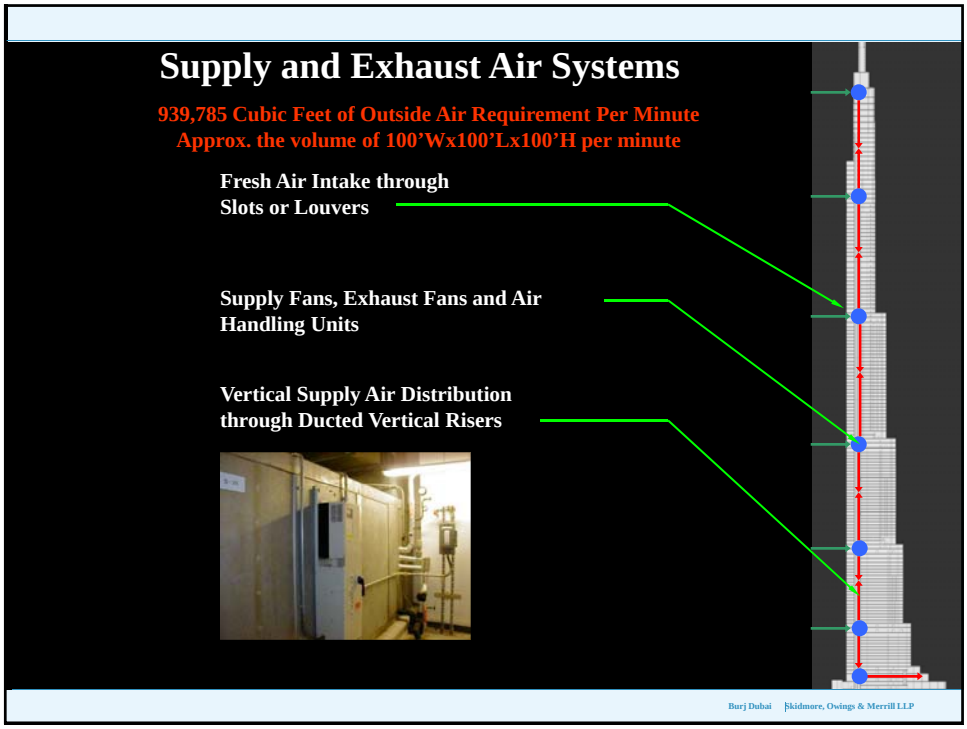
101 F

115 F

Taking Advantage of Height: Building in the Clouds?

What else might designers try to take advantage of

- Gravity
- Building Movement
- Stack Effect
- Electrical Potential

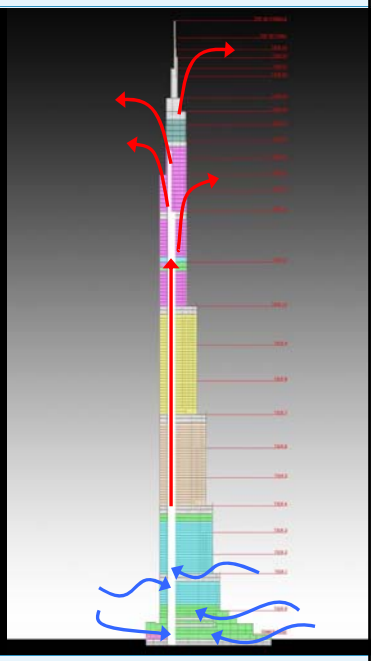

Supply and Exhaust Air Systems
939,785 Cubic Feet of Outside Air Requirement Per Minute
Approx. the volume of 100'Wx100'Lx100'H per minute
Fresh Air Intake through Slots or Louvers
Supply Fans, Exhaust Fans and Air Handling Units
Vertical Supply Air Distribution through Ducted Vertical Risers
Burj Dubai
Skidmore, Owings & Merrill LLP

Stack Effect

Also known as chimney effect

Occurs when temperature difference between exterior and interior air induces air movement

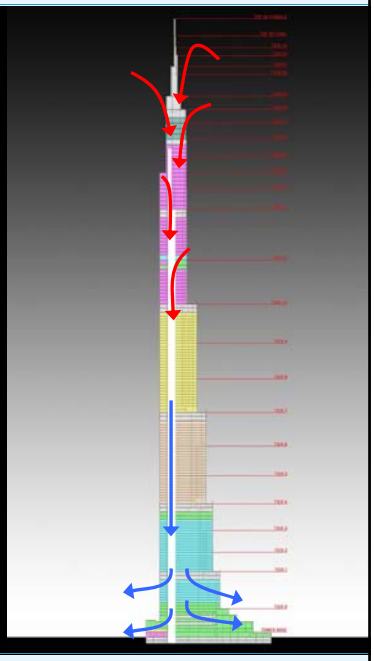
In a cold climate, warmer inside air rises through building, colder outside air rushes in at the base



Burj Dubai Skidmore, Owings & Merrill LLP

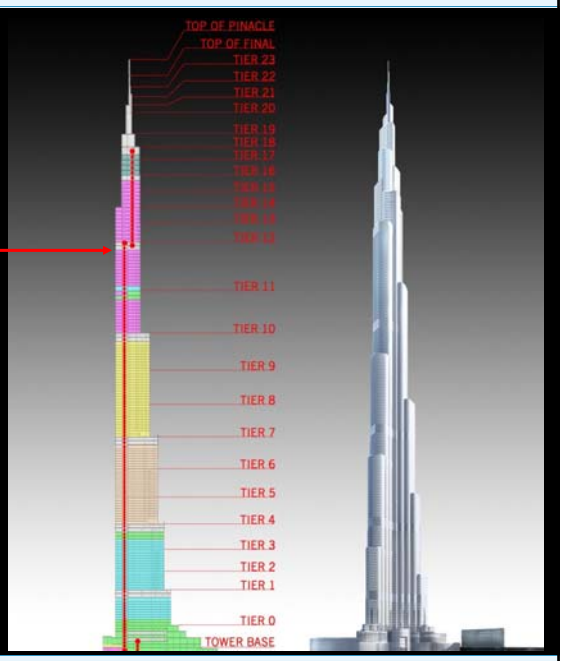
Stack Effect Mitigation

- Process is reversed in a hot climate like Dubai:
- colder air inside falls, drawing in hot outside air at top of the building
- Mitigated through:
  - Revolving doors/air locks/gaskets
  - Mechanical systems balancing
  - Air-tight construction of continuous shafts and exterior wall
  - Interruption of continuous shafts through use of:
    - Air locks
    - Revolving doors
    - Intermediate level lobbies



Burj Dubai Skidmore, Owings & Merrill LLP

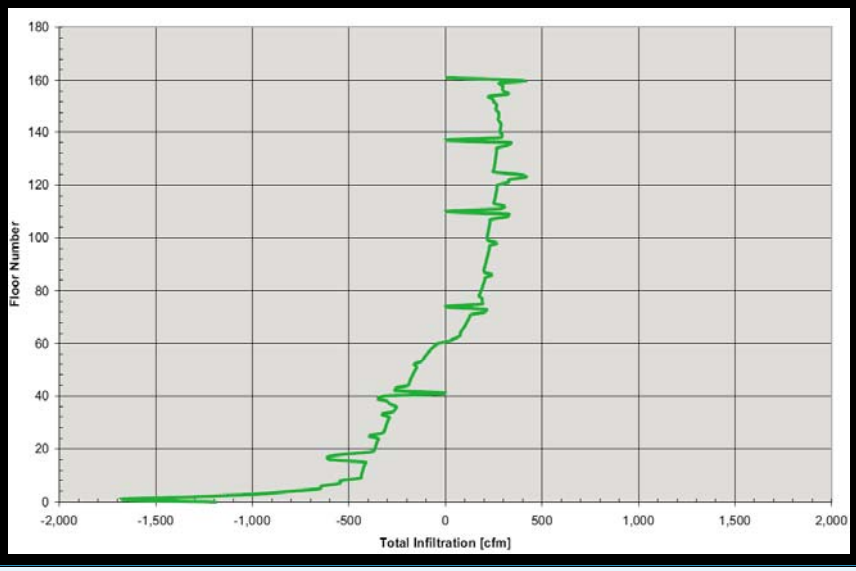
Elevator BS-1,
transfer at 138



Burj Dubai Skidmore, Owings & Merrill LLP

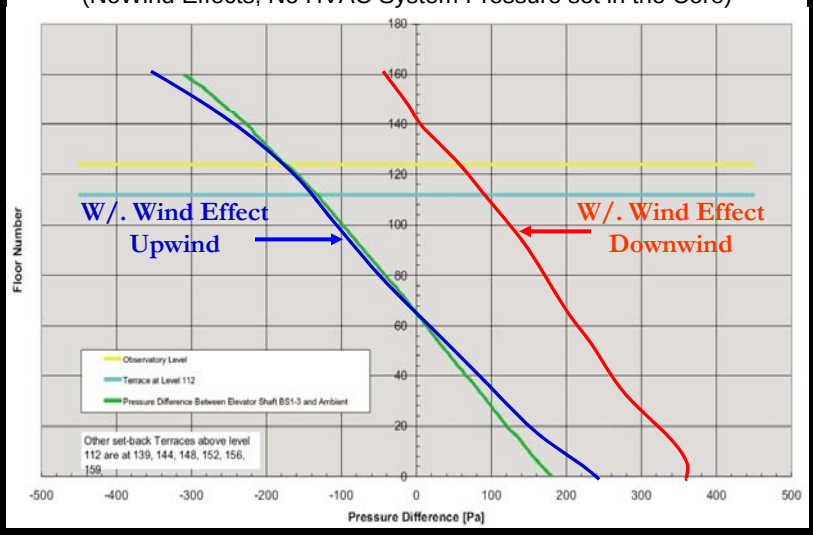
Total Infiltration onto Floor

(NoWind Effects, No HVAC System Pressure set in the core)



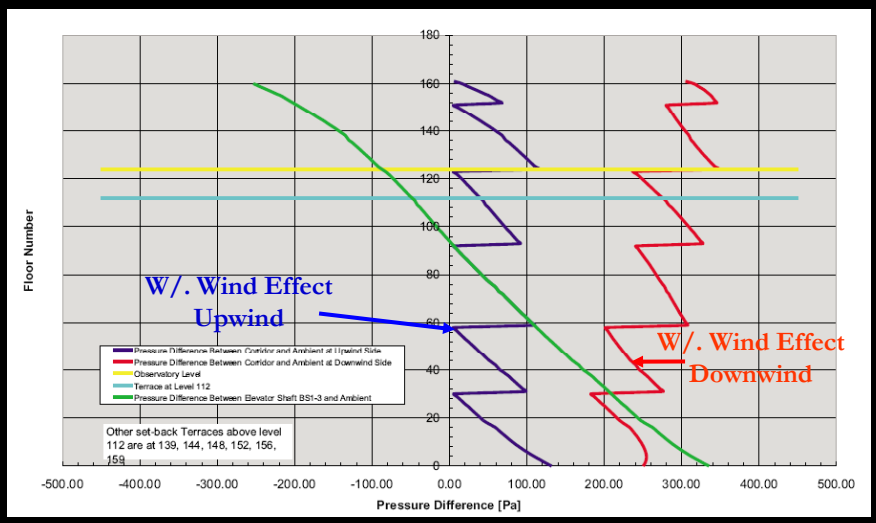
Burj Dubai Skidmore, Owings & Merrill LLP

Pressure Differences Between Inner Core and Ambient Conditions
(NoWind Effects, No HVAC System Pressure set in the Core)

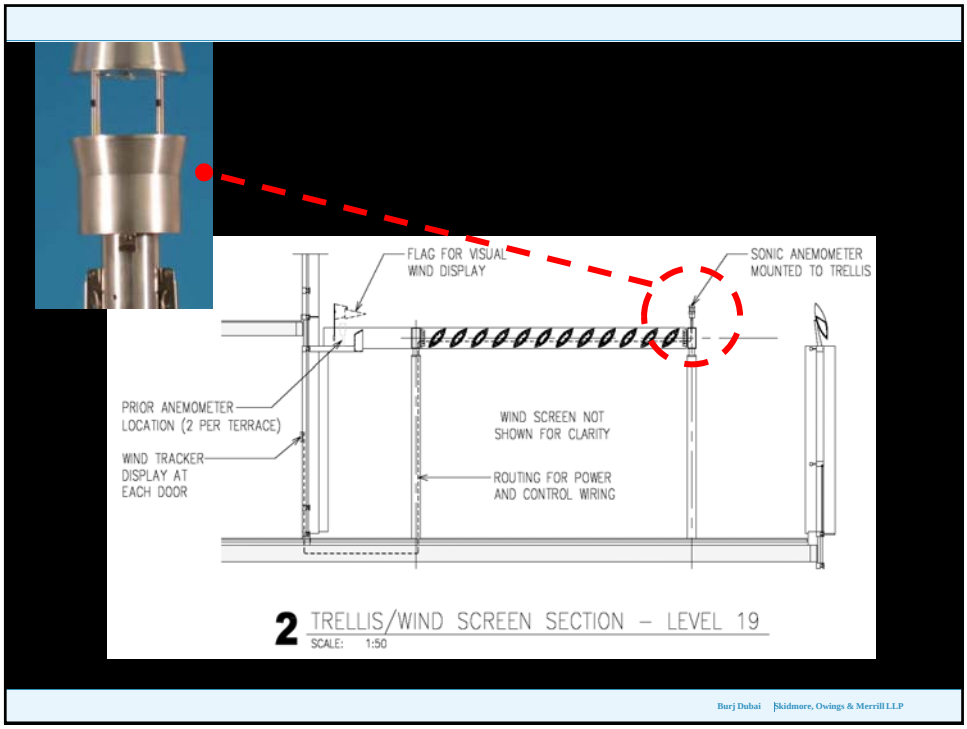


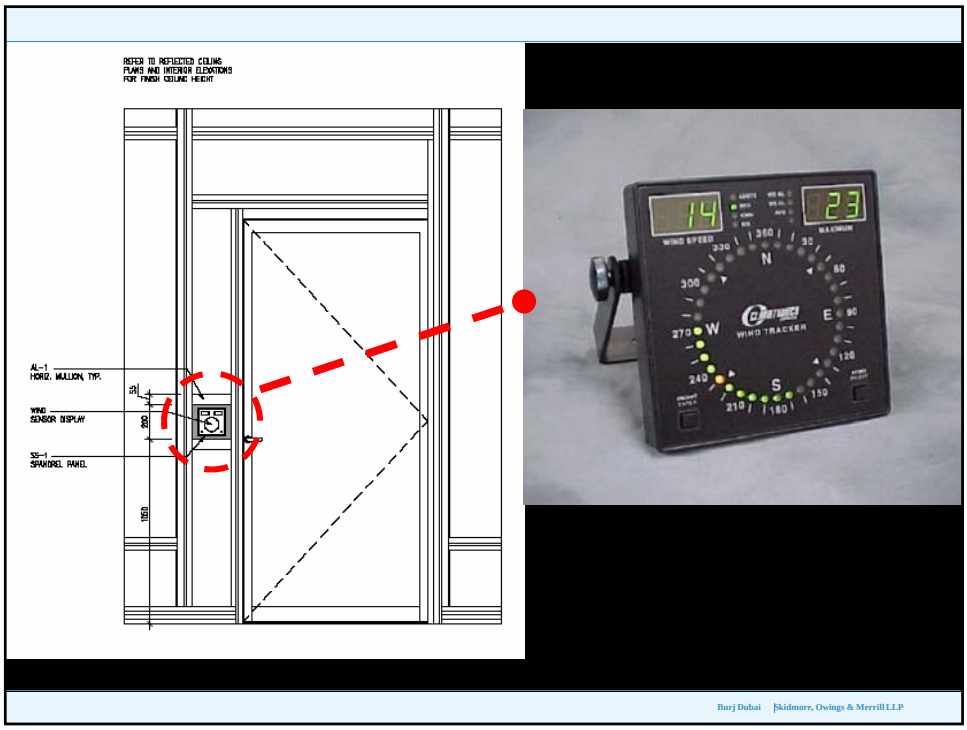
Burj Dubai Skidmore, Owings & Merrill LLP

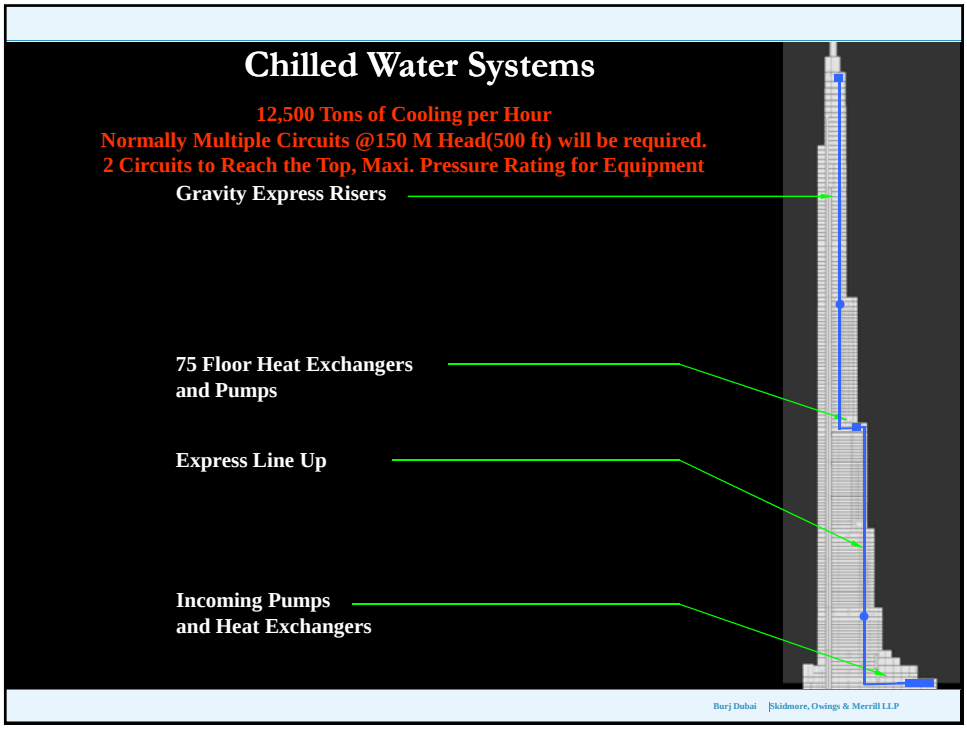
Pressure Differences Between Inner and Ambient Conditions
(W/. Wind Effects and HVAC System Pressure set in the Core)

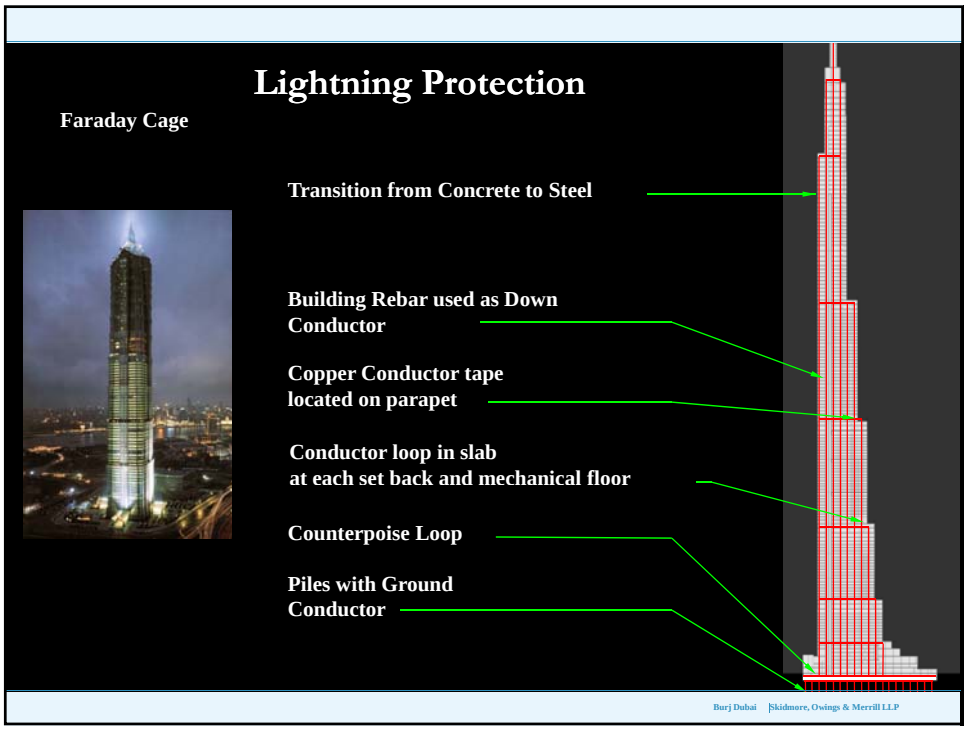


Burj Dubai Skidmore, Owings & Merrill LLP


FLAG FOR VISUAL WIND DISPLAY
SONIC ANEMOMETER MOUNTED TO TRELLIS
PRIOR ANEMOMETER LOCATION (2 PER TERRACE)
WIND TRACKER DISPLAY AT EACH DOOR
WIND SCREEN NOT SHOWN FOR CLARITY
ROUTING FOR POWER AND CONTROL WIRING
2 TRELLIS/WIND SCREEN SECTION – LEVEL 19
SCALE: 1:50
Burj Dubai Skidmore, Owings & Merrill LLP


REFER TO REFLECTED CEILING PLANS AND INTERIOR ELEVATIONS FOR FINISH CEILING HEIGHT
AL-1 HORIZ. MULLION, TYP.
WIND SENSOR DISPLAY
SS-1 SPANDREL PANEL
14
23
WIND SPEED
MAXIMUM
N
E
S
W
WIND TRACKER
Burj Dubai Skidmore, Owings & Merrill LLP


Chilled Water Systems
12,500 Tons of Cooling per Hour
Normally Multiple Circuits @150 M Head(500 ft) will be required.
2 Circuits to Reach the Top, Maxi. Pressure Rating for Equipment
Gravity Express Risers
75 Floor Heat Exchangers
and Pumps
Express Line Up
Incoming Pumps
and Heat Exchangers
Burj Dubai
Skidmore, Owings & Merrill LLP


Lightning Protection
Faraday Cage
Transition from Concrete to Steel
Building Rebar used as Down
Conductor
Copper Conductor tape
located on parapet
Conductor loop in slab
at each set back and mechanical floor
Counterpoise Loop
Piles with Ground
Conductor
Burj Dubai
Skidmore, Owings & Merrill LLP

Andrew Alleyne **University of Illinois** **alleyne@illinois.edu**

Andrew Alleyne earned his BSE in mechanical/aerospace engineering from Princeton University, and his MSE and PhD in mechanical engineering from University of California at Berkeley. He joined mechanical engineering faculty at Illinois in 1994, and he was named the Ralph M. and Catherine V. Fisher Professor in 2002. He currently serves as the Associate Dean for Research in the College of Engineering.

Prof. Alleyne's research addresses a range of issues within controls: the analysis and design of control systems in a dimensionless framework, advanced motion control through iterative learning control and adaptive feedforward techniques, and robust control approaches to gain-scheduling as they relate to energy systems and fluid power.

Anu Annaswamy **Massachusetts Institute of Technology** **aanna@mit.edu**

Dr. Annaswamy received the Ph.D. degree in Electrical Engineering from Yale University in 1985. She has been a member of the faculty at Yale, Boston University, and MIT where currently she is the director of the Active-Adaptive Control Laboratory and a Senior Research Scientist in the Department of Mechanical Engineering. Her research interests pertain to adaptive control theory and applications to aerospace and automotive control, active control of noise in thermo-fluid systems, active emission control, control of autonomous systems, control of smart grid-oriented markets and integration with renewables, and co-design of control and implementation in smart buildings. She has authored numerous journal and conference papers and a graduate textbook on adaptive systems. Dr. Annaswamy has received several awards including the George Axelby Outstanding Paper award from the IEEE Control Systems Society, the Presidential Young Investigator award from the National Science Foundation, and the Hans Fisher Senior Fellowship from the Institute for Advanced Study at the Technische Universität München. Dr. Annaswamy is a Fellow of the IEEE and a member of AIAA.

Panos Antasakolis **Notre Dame** **antsaklis.1@nd.edu**

Panos Antsaklis is the Brosey Professor of Electrical Engineering at the University of Notre Dame. He is a graduate of the National Technical University of Athens, Greece, and holds MS and PhD degrees from Brown University. His research addresses problems of control and automation and examines ways to design control systems that will exhibit high degree of autonomy. His recent research focuses on networked embedded systems and addresses problems in the interdisciplinary research area of control, computing and communication networks, and on hybrid and discrete event dynamical systems. He had co-authored two research monographs on discrete event systems, two graduate textbooks on Linear Systems and has co-edited six books on Intelligent Autonomous Control, Hybrid Systems and Networked Embedded Control Systems. He is an IEEE Fellow and the 2006 recipient of the Engineering Alumni Medal of Brown University. He is the Editor-in-Chief of the IEEE Transactions on Automatic Control.

Dhiraj Arora **GE Research** **arora@research.ge.com**

Dhiraj is a control systems engineer in Automations and Controls Laboratory at GE Global Research Center. He joined GE in 2005 and since then has worked on controls and estimation problems in various fields such as aircraft engines, wind turbines, ultrasound therapeutics, and building energy management systems. Dhiraj holds a doctorate in Mechanical Engineering with emphasis on design of control systems.

John Beane **Honeywell** **john.bean@honeywell.com**

John Beane is the research manager for Knowledge Services in the Honeywell Automation and Controls Solutions Lab. Honeywell is a global leader in the energy space. Honeywell is working closely with the utilities to develop cost-effective ways to connect homes and buildings to the Smart Grid. Related research topics include: wind farm CBM, predicting wind output, optimizing sources and loads to manage a building microgrid, home energy manager, ADR for buildings and homes, energy data visualization, using data to change human behavior, smart grid communications standards, building energy modeling and simulation, building energy efficiency, mobile tools for building operations and BIM.

Francesco Borelli **University of California Berkeley** **fborrelli@me.berkeley.edu**

Francesco Borrelli received the `Laurea' degree in computer science engineering in 1998 from the University of Naples `Federico II', Italy. In 2002 he received the PhD from the Automatic Control Laboratory at ETH-Zurich, Switzerland. He is currently an Assistant Professor at the Department of Mechanical Engineering of the University of California at Berkeley, USA. He is the author of more than fifty publications and in the field of predictive control. He is author of the book Constrained Optimal Control of Linear and Hybrid Systems published by Springer Verlag, the winner of the `Innovation Prize 2004' from the ElectroSwiss Foundation and the winner of the 2009 NSF CAREER award. In 2008 he was appointed the chair of the IEEE technical committee on automotive control. His research interests include constrained optimal control, model predictive control and its application to advanced automotive control and energy efficient building operation. For more info visit: www.mpc.berkeley.edu

---

James Botic **Johnson Controls Inc.** **james.s.botic@jci.com**

James S. Botic, Received his BSEE in 1967 from the University of Wisconsin Madison, and his MSEE – 1972, PhD in 1983 from the University of Wisconsin Milwaukee. He is currently the Director of Controls Research Building Efficiency and the Chief Architect for Metasys Building Automation System.

Jim Braun **Purdue University** **jbraun@purdue.edu**

Dr. Braun has worked in the field of air conditioning and refrigeration for over 30 years in both university and industrial settings. His practical experience includes working as a development engineer for advanced cooling equipment, a software developer for simulation tools in modeling buildings and large-scale heating and cooling plants, a developer of intelligent control algorithms for large commercial energy management and control systems, and group manager for controls research. He has been awarded four patents. His research combines the use of computer modeling, optimization, and experiments to study and improve the performance of thermal systems. Overall, Dr. Braun has led or been involved with proposals leading to research awards totaling over $20 million and has over 200 papers journal and conference papers published or in review, five of which received best paper awards. Within ASHRAE, Dr. Braun has been chairman of technical committees on “Smart Building Systems” and “Building Operation Dynamics” and is currently Vice-Chair for the Research Administration Committee. He is an Associate Editor for the International Journal of HVAC&R Research. He is a Fellow within ASHRAE and has received the ASHRAE Distinguished Service Award, the E.K. Campbell Award of Merit, in recognition of outstanding service and achievement in teaching and/or research in subjects relating to the industry and professions represented by ASHRAE, and the Early Achievement Award from the International Building Performance Simulation Association.

Francesco Bullo **University of California Santa Barbara** **bullo@engineering.ucsb.edu**

Francesco Bullo is a Professor with the Mechanical Engineering Department at the University of California, Santa Barbara. He received the Laurea degree "summa cum laude" in Electrical Engineering from the University of Padova, Italy, in 1994, and the Ph.D. degree in Control and Dynamical Systems from the California Institute of Technology in 1999. From 1998 to 2004, he was an Assistant Professor with the Coordinated Science Laboratory at the University of Illinois at Urbana- Champaign.

Steven Bushby **National Institute of Standards and Technology** **steven.bushby@nist.gov**

Mr. Bushby is the leader of the Mechanical Systems and Controls Group and the Embedded Intelligence in Buildings Program in the Building and Fire Research Laboratory at the National Institute of Standards and Technology. He is responsible for overseeing research activities related to the development of national and international standards for integrated building automation systems, automated fault detection and diagnostics for HVAC system components, automated commissioning tools for HVAC control systems, integration of building control systems with the Smart Grid, and developing a testbed for studying the interaction of multiple building control systems in "cybernetic" buildings.

Amit Chakraborty **Siemens Corporation, Corporate Research** **amit.chakraborty@siemens.com**

Dr. Amit Chakraborty leads the Data Modeling and Optimization Program at Siemens Corporate Research. He received his PhD in Electrical Engineering from Yale University. Prior to that, he obtained his MS and M.Phil in Electrical Engineering also from Yale and his B.Tech in Electronics and Electrical Communication Engineering from the Indian Institute of Technology. He joined Siemens Corporate Research right after his PhD 1996 as a Member of Technical Staff, was subsequently promoted to a Project Manager then to a Senior Member of Technical Staff and to a Program Manager, a position he has held since 2005 to lead the Data Modeling and Optimization program. With a team of 35-40 research scientists, engineers and students, the program focuses primarily on Data Mining and Optimization applications across all three sectors in Siemens, Industry, Healthcare and Energy. He has successfully led several Research and Development projects in Energy Management such as Total Plant Optimization for High Performance Buildings, Parametric Fault Diagnostics for Gas Turbines, Power Flow Optimization for Electric Grids, Semantic Data Modeling for Power Systems etc. His team is also engaged in a several large government R&D projects in collaboration with leading universities. Dr. Chakraborty has mentored many employees, and PhD and Masters students. He has 15 granted and many more pending patents and has also published in respected journals and conferences.

Emmanuel Collins **Florida State** **ecollins@eng.fsu.edu**

Geir Dullerud **University of Illinois** **dullerud@illinois.edu**

Geir E. Dullerud is Professor of Mechanical Engineering, and Research Professor of the Coordinated Science Laboratory, at the University of Illinois at Urbana-Champaign. Prior to this he was on faculty in Applied Mathematics at the University of Waterloo 1996-1998, after being a Research Fellow at the California Institute of Technology from 1994-1995, in the Control and Dynamical Systems Department. During the academic year 2005-2006 he held a visiting faculty position at Stanford University in Aeronautics and Astronautics. He has published two books: "A Course in Robust Control Theory", Texts in Applied Mathematics, Springer, 2000, and "Control of Uncertain Sampled-data Systems", Birkhauser 1996. His areas of current research interest include networked and cooperative control, robotic vehicles, complex and hybrid dynamical systems. In 1999 he received the CAREER Award from the National Science Foundation, and in 2005 the Xerox Faculty Research Award at UIUC. He is a Fellow of the IEEE.

Brian Fabien **University of Washington** **fabien@u.washington.edu**

Professor Brian C, Fabien: Department of Mechanical Engineering, University of Washington, Seattle, WA 98195. Professor Fabien received his Ph.D. in Mechanical Engineering from Columbia University in 1990. His research interest include; (i) the modeling of multi-discipline dynamic systems, (ii) nonlinear optimal control theory and computation; and (iii) the development of energy storage technologies.

Brian Fiegan **Trane** **bfiegen@trane.com**

Brian Fiegen, Global Systems Applications Leader, is responsible for Trane's Applications Engineering, Systems Marketing, and C.D.S. (Customer Direct Service) groups. He joined Trane in 1983 immediately following graduation from college. Brian has held a number of airside product management positions throughout his career including Climate ChangerTM Air Handlers and VariTraneTM Variable Air Volume products and controls. He has been involved with product development and promotion of air handling and distribution products, systems, and controls throughout much of that time. Today his groups actively help customers apply HVAC products and controls into systems to meet various performance needs as well as deal with key industry issues such as IAQ and sustainable construction.

Brian received his Bachelor of Science Degree in Mechanical Engineering from South Dakota School of Mines and Technology in Rapid City, SD and he is a member of ASHRAE.

Matthew Franchek **University of Houston** **mfranchek@central.uh.edu**

Matthew Franchek is Professor of Mechanical Engineering Department and of Biomedical Engineering at the University of Houston. He received his BS degree (1986) in Mechanical Engineering from the University of Texas at Arlington, and his MS (1987) and PhD (1991) in Mechanical Engineering from Texas A&M University. His expertise includes nonlinear dynamics, linear/nonlinear control theory for scalar and multivariable systems, and system identification. His research is directed toward accurate systems diagnostics, prognostics and the cooperative robust integration of engineered systems. The application areas include internal combustion engines, subsea systems and artificial organs. He was advised over 15 PhD students, 25 MS students and is the author of over 120 peer reviewed publications.

Brandon Hencey **Cornell University** **bhencey@gmail.com**

Brandon Hencey is an assistant professor in the Sibley School of Mechanical and Aerospace Engineering at Cornell University. Recent work includes model predictive control of a campus chilled water plant with thermal energy storage and system theoretic results for interpolated controller synthesis via convex optimization. His research interests also include constructive methods for distributed synthesis of complex control systems. Dr. Hencey held a postdoctoral position at United Technologies Research Center after receiving his Ph.D. from the University of Illinois.

Jungho Kim **Univesity of Maryland** **kimjh@umd.edu**

Jungho Kim holds a professorship in the Dept. of Mechanical Engineering at the U. of Maryland. He has performed extensive research in heat and mass transfer with support from NASA, NSF, ONR, NIST, AFRL, NSA and private companies that has resulted in over 110 journal and refereed conference publications . He is an associate editor for the Int. Journal of Multiphase Flow, and is a past chair of the ASME K-13 committee on Multiphase Heat Transfer. His work in building energy focuses on control using multiple wireless sensors, and prediction of building thermal response to predicted weather conditions.

Miroslav Krstic **University of California San Diego** **krstic@ucsd.edu**

Miroslav Krstic is the Daniel L. Alspach Professor at UC San Diego and the founding director of the Cymer Center for Control Systems and Dynamics. He is a co-author of eight books, including Nonlinear and Adaptive Control Design (1995), which is one of the two most cited research monographs in the history of control engineering, the new single-authored Delay Compensation for Nonlinear, Adaptive, and PDE Systems (2009), and six other books on control of turbulent fluid flows, stochastic nonlinear systems, and extremum seeking. Krstic has held the Russell Severance Springer Distinguished Visiting Professorship at UC Berkeley and the Harold W. Sorenson Distinguished Professorship at UC San Diego. He is a recipient of the ONR Young Investigator, PECASE, and NSF Career Awards, as well as the Axelby and Schuck Paper Prizes. Krstic was the first recipient of the UCSD Research Award from the area of engineering. He is a Fellow of IEEE and IFAC. Krstic serves as Senior Editor in IEEE Transactions on Automatic Control and Automatica and as Editor of the Springer-Verlag book series Communications and Control Engineering.

Luke Leung **Skidmore, Owings & Merrill LLP** **Luke.Leung@som.com**

As Associate Director and leader of the Sustainable Engineering Studio, Luke Leung is responsible for systems design and specifications from conception to construction for many commercial and institutional projects including Burj Khalifa, the world's tallest building. He has designed many LEED® projects, ranging from certified to LEED® Platinum, including the second largest LEED® certified building, McCormick Place West.

Colin McCormick **Department of Energy** **Colin.McCormick@ee.doe.gov**

Dr. Colin McCormick is a Senior Technical Advisor to the Assistant Secretary of Energy Efficiency and Renewable Energy at the Department of Energy. Prior to joining the Department he was an energy and security analyst at the Federation of American Scientists, a staff member with the House Science and Technology Committee, and a AAAS Congressional Fellow on the staff of Rep. Ed Markey of Massachusetts. Dr. McCormick received his PhD in atomic and optical physics from the University of California, Berkeley, and did post-doctoral work in quantum optics at the National Institute of Standards and Technology (NIST) in the group of 1997 Physics Nobel Laureate William Phillips.

Prashant Mehta **University of Illinois** **mehtapg@illinois.edu**

Prashant Mehta is an Assistant Professor at the Department of Mechanical Science and Engineering, University of Illinois at Urbana-Champaign. He received his Ph.D. in Applied Mathematics from Cornell University in 2004. Prior to joining UIUC, he was a Research Engineer at the United Technologies Research Center (UTRC). His research interests are at the intersection of dynamical systems and control theory, including fundamental limitations in nonlinear control, model reduction of Markov chains, phase transition and learning in large population games.

Prashant Mehta received the Outstanding Achievement Award at UTRC for his contributions to modeling and control of combustion instabilities in jet-engines. His students received the Best Student Paper Award at the IEEE Conference on Decision and Control 2007 and 2009.

William Messner **Carnegie Mellon** **bmessner@andrew.cmu.edu**

Satish Narayan **United Technologies Corporation** **NarayaS@utrc.utc.com**

Satish Narayanan earned his degrees in Mechanical Engineering starting with B.E. (Hons.) from the Birla Institute of Technology and Science (Pilani, India), and then did his M.S and Ph.D at University of Houston. He currently leads R&D programs in high performance building systems in the Energy Systems Program Office at UTRC. Since joining UTRC in 1998, he has worked in a broad range of problems involving physics-based modeling, experimentation and control of nonlinear dynamic phenomena in aerospace and building systems. He has published over 12 archival journal articles and over 30 conference papers, and received 4 patents.

Huei Peng **University of Michigan** **hpeng@umich.edu**

Huei Peng is currently a Professor of the Department of Mechanical Engineering, and the Executive Director of Interdisciplinary and Professional Engineering, at the University of Michigan, Ann Arbor. His research interests include adaptive control and optimal control, with emphasis on their applications to vehicular and transportation systems. His current research focuses include design and control of hybrid electric vehicles and vehicle active safety systems. He has more than 180 technical publications, including 70 in referred journals and transactions.

Brian Rasmussen **Texas A & M** **bryan.rasmussen@gmail.com**

Bryan Rasmussen received his B.S. degree magna cum laude in Mechanical and Aerospace Engineering from Utah State University in 2000. He was awarded M.S. and Ph.D. degrees in Mechanical Engineering from the University of Illinois at Urbana-Champaign in 2002 and 2005. He is currently an Assistant Professor of Mechanical Engineering at Texas A&M University, researching dynamic modeling and control of thermo-fluid energy systems. He was awarded the NSF CAREER and the ASHRAE Young Investigator awards for research, and is the recipient of several university and national teaching awards. He is a member of Tau Beta Pi, ASME, ASHRAE and IEEE. He and his wife Holly are the proud parents of five children.

Mario Rotea **University of Texas - Dallas** **rotea@utdallas.edu**

Mario A. Rotea graduated with a degree in electronic engineering from the University of Rosario in 1983. He received the master's degree in electrical engineering in 1988 and the Ph.D. in control science and dynamical systems in 1990 from the University of Minnesota. He is currently a professor and head of the Mechanical Engineering Department at the University of Texas at Dallas, where he is also a professor of electrical engineering. He began his academic career at Purdue University, West Lafayette, where he was a professor of aeronautics and astronautics for seventeen years. He was a professor and head of the Mechanical and Industrial Engineering Department from 2007 to 2009 at the University of Massachusetts, Amherst. He managed the Control Systems program at the NSF from 2005 to 2007 and worked for the United Technologies Research Center in 1997–1998. Dr. Rotea has made has pioneering contributions in optimal and robust control systems. He has developed and transitioned to industry control systems to mitigate noise and vibrations in gas turbine engines, helicopters, and machine tools. He is a Fellow of the IEEE. His current research interests are in monitoring and control of energy conversion systems.

Sarah Ryker **Science & Technology Policy Institute** **sryker@ida.org**

Sarah J. Ryker analyzes energy and environmental policy at the Science and Technology Policy Institute, a federally funded research and development center with a Congressional charter to advise the White House Office of Science and Technology Policy. Her PhD is from Carnegie Mellon's Department of Engineering and Public Policy, where she developed technical and decision-analytic methods to prioritize federal research and regulation of drinking water. Prior to her PhD, she spent 13 years as a researcher and research manager with the US Geological Survey.

Marty Savoie **US CoE CERL** **Martin.J.Savoie@usace.army.mil**

Kim Stelson **University of Minnesota** **kstelson@me.umn.edu**

Kim A. Stelson is Director of the NSF-funded Engineering Research Center for Compact and Efficient Fluid Power. He is a Professor in the Department of Mechanical Engineering at the University of Minnesota where he has been since 1981. He received his B.S. degree in mechanical engineering from Stanford University in 1974 and his S.M. and Sc.D. degrees in mechanical engineering from M.I.T. in 1977 and 1982. Before becoming involved in fluid power research, Stelson was active in research in the modeling and control of manufacturing processes, especially metal forming, polymer processing and composite materials manufacturing. He has been a visiting faculty member at Hong Kong University of Science and Technology, the University of Auckland and the University of Bath. He has previously been Director of the Design and Manufacturing Division and Director of Graduate Studies for the M.S. in Manufacturing Systems Program at the University of Minnesota. Stelson is Associate Technical Editor of the Journal of Dynamic Systems, Measurement and Control, a journal that has twice awarded him the best paper award. He is a Fellow of the American Association for the Advancement of Science.

Jakob Stoustrup **Aalborg University** **jakob@es.aau.dk**

Jakob Stoustrup received his MSc degree in EE in 1987, and the PhD degree in Applied Mathematics in 1991, both from the Technical University of Denmark. In the period 1991–1996, Jakob Stoustrup held several positions at the Department of Mathematics, Technical University of Denmark. He has been a Visiting Professor atthe University of Strathclyde, Glasgow, UK, and at the Mittag-Leffler Institute, Stockholm, Sweden. Since 1997 he was a Professor at Automation & Control, Aalborg University, Denmark, and since 2006 was Head of Research for the Department of Electronic Systems. He has acted as Associate Editor, Guest Editor and Editorial Board Member of several international journals. He is an IEEE SM, and has been Chairman of an IEEE CSS/RAS Joint Chapter. Since 2008, he has been Chairman for the IFAC Technical Committee SAFEPROCESS. He has received the Statoil Prize, the Dannin Award for Scientific Research, and is a member of The Danish Academy of Technical Sciences. The main contributions of Stoustrup have been to robust control theory and to the theory of fault tolerant control systems, with more than 200 peer-reviewed scientific papers. Recently, Prof. Stoustrup has proposed the so-called plug-and-play control framework. Apart from the theoretical work, he has carried out industrial applications in cooperation with more than 50 industrial companies.

Greg Washington **The Ohio State University** **washington.88@osu.edu**

John Wen **Rensselaer Polytechnic Institute** **wenj@rpi.edu**

John T. Wen received his B.Eng. from McGill University in 1979, M.S. from University of Illinois in 1981, and Ph.D. from Rensselaer Polytechnic Institute in 1985, all in Electrical Engineering. From 1981-1982, he was a system engineer at Fisher Controls. From 1985-1988, he was a member of technical staff at the Jet Propulsion Laboratory. Since 1988, he has been with Rensselaer Polytechnic Institute where he is currently a professor in the Department of Electrical, Computer, and Systems Engineering with a joint appointment in the Department of Mechanical, Aerospace, and Nuclear Engineering. He was appointed in 2005 as the Director of a New York State sponsored interdisciplinary research center, Center for Automation Technologies and Systems (CATS). He was an ASEE/NASA Summer Faculty Fellow in 1993, a JSPS Senior Visiting Scientist in 1997, and an Oversea Assessor for the Chinese Academy of Sciences from 2004-2009. His research interest is in dynamical systems modeling and control with applications to vibration suppression, robot manipulation, opto-mechatronics systems, thermal management, and flow control. He is a Fellow of IEEE since 2001.

Michael Wetter **Lawrence Berkeley National Laboratory** **MWetter@lbl.gov**

Michael Wetter is a Computational Scientist in the Simulation Research Group at Lawrence Berkeley National Laboratory (LBNL). His research includes integrating building performance simulation tools into the research process, as well as their use for design and operation of buildings. At LBNL, he is developing the Modelica Buildings library for building energy and control systems, the Building Controls Virtual Test Bed software for co-simulation and model-based operation, and the GenOpt optimization program. Prior to joining LBNL, he led the development of building system models at the United Technologies Research Center (UTRC). He did his dissertation at the University of California at Berkeley and at LBNL, where he created the GenOpt optimization program and the BuildOpt building simulation program and where he developed the first building energy optimization technique that provably converges to the optimal building design. He is a recipient of the bi-annual Outstanding Young Contributor Award of the International Building Performance Simulation Association (IBPSA), the vice president of IBPSA-USA and a member of ASHRAE.

Fumin Zhang **Georgia Tech** **fumin@gatech.edu**

Dr. Fumin Zhang received the B.S. and M.S. degrees from Tsinghua University, Beijing, China, in1995 and 1998, respectively, and the Ph.D. degree from the Department of Electrical and Computer Engineering, University of Maryland, College Park, in 2004. He has been an Assistant Professor in the School of ECE, Georgia Institute of Technology (Georgia Tech), Atlanta, since 2006. He was a Lecturer and Postdoctoral Research Associate in the Mechanicaland Aerospace Engineering Department, Princeton University, Princeton, NJ, from 2004 to 2006. He worked for the Institute for Systems Research, University of Maryland. He founded the research and teaching program in the fields of robotics and control at Georgia Tech Savannah Campus. His major research focus includes design and control of underwater robots and mobile sensor networks, battery modeling and control, and theoretical foundations for cyber-physical systems. He received the NSF CAREER award in September, 2009, the ONR YIP Award in April, 2010, and the Lockheed Inspirational Young Faculty Award in May, 2010.