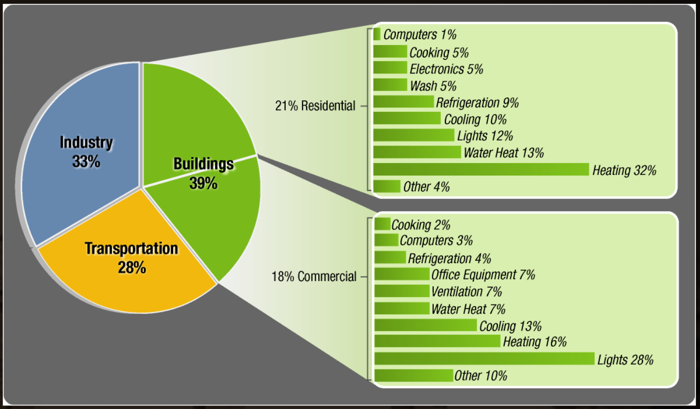
Building Energy Demand Challenge

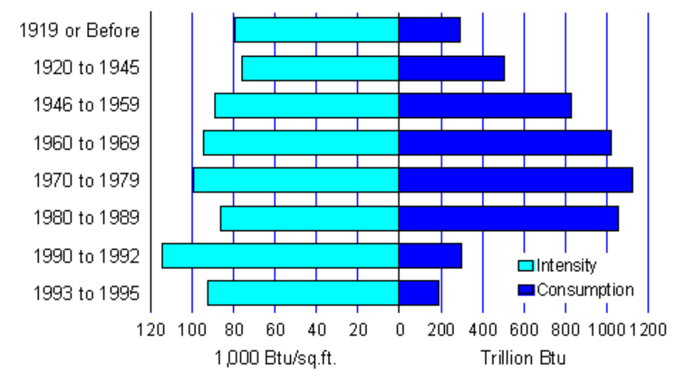
- Buildings consume
  - 39% of total U.S. energy
  - 71% of U.S. electricity
  - 54% of U.S. natural gas
- Building produce 48% of U.S. carbon emissions
- Commercial building annual energy bill: $120 billion
- The only energy end-use sector showing growth in energy intensity
  - 17% growth 1985 - 2000
  - 1.7% growth projected through 2025

Sources: Ryan and Nicholls 2004, USGBC, USDOE 2004

Energy Breakdown by Sector



Energy Intensity by Year Constructed



Energy Information Administration
1995 Commercial Buildings Energy Consumption Survey

Key Points

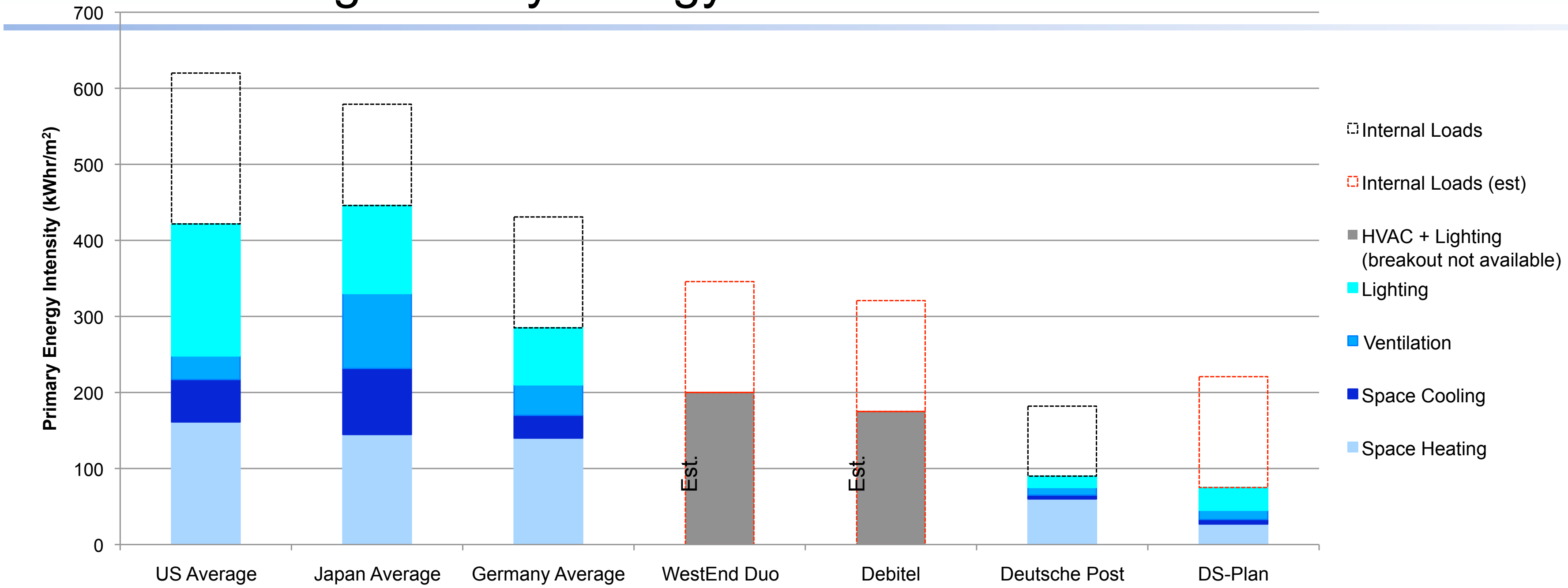
- Energy efficient buildings. **Achieving >50% over current standards (ASHRAE 90.1) is possible;** proof points occur for all sizes and climates; buildings designed using climate responsive design principles.

- Market conditions – currently **driven** by labeling **and increasingly by regulatory pressures** (carbon cost not sufficient to drive market: findings through UTC led WBCSD study).

- What is hard? **Delivery process handoffs are a problem** and are where there is a loss of potential for energy savings in design, construction and operation.

- What are R&D areas?
  - Address Productivity – **need design tools** (configuration exploration, specification of equipment and controls, automated implementation) – for automation on all parts of delivery chain.
  - Address Risk. Need calibrated models (experimental facilities) **and ability to calculate, track and manipulate uncertainty (DFSS).**
  - Address Operations – need to understand sensing requirements, **failure modes** and FDIA.

Office Building Primary Energy Intensities



HIGHLY EFFICIENT BUILDINGS EXIST

Energy Retrofit
10-30% Reduction

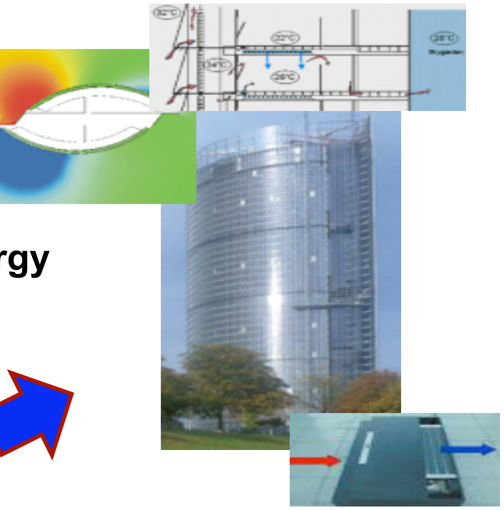
Cityfront Sheraton
Chicago IL
1.2M ft^2, 300 kWhr/m^2
5753 HDD, 3391 CDD
VS chiller, VFD fans, VFD pumps
Condensing boilers & DHW

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

Very Low Energy
>50% Reduction

LEED Design
20-50% Reduction

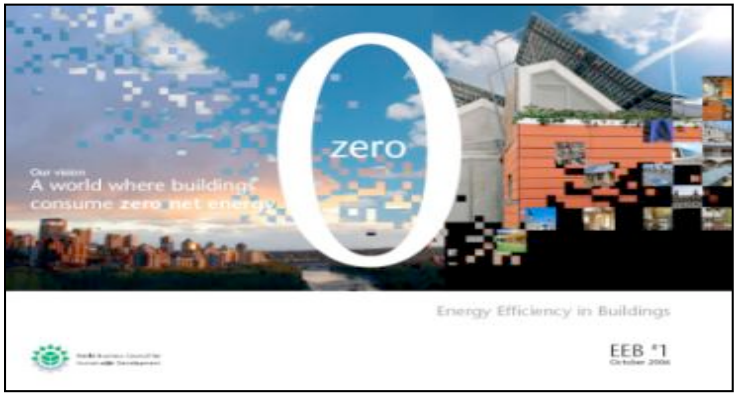
Tulane Lavin Bernie
New Orleans LA
150K ft^2, 150 kWhr/m^2
1513 HDD, 6910 CDD
Porous Radiant Ceiling, Humidity Control Zoning,
Efficient Lighting, Shading



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

WBCSD EEB PROJECT

A world where buildings consume zero net energy


Our vision
A world where buildings consume zero net energy
zero
Energy Efficiency in Buildings
EEB *1

Energy efficiency first

From the business voice

Launch and lead sector transformation

Contribution to “sustainable” buildings

Communicate openly with markets

LAFARGE

World Business Council for Sustainable Development

United Technologies

ArcelorMittal

DUPONT The miracles of science

BOSCH

SKANSKA

ACTELIOS GRUPPOFALCK

PHILIPS

CEMEX

THE KANSAI ELECTRIC POWER CO.,INC.

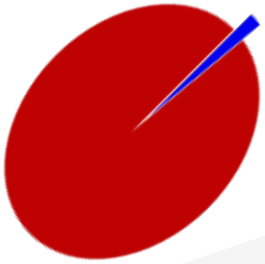
GDF SUEZ

TEPCO

EDF

SONAE SIERRA

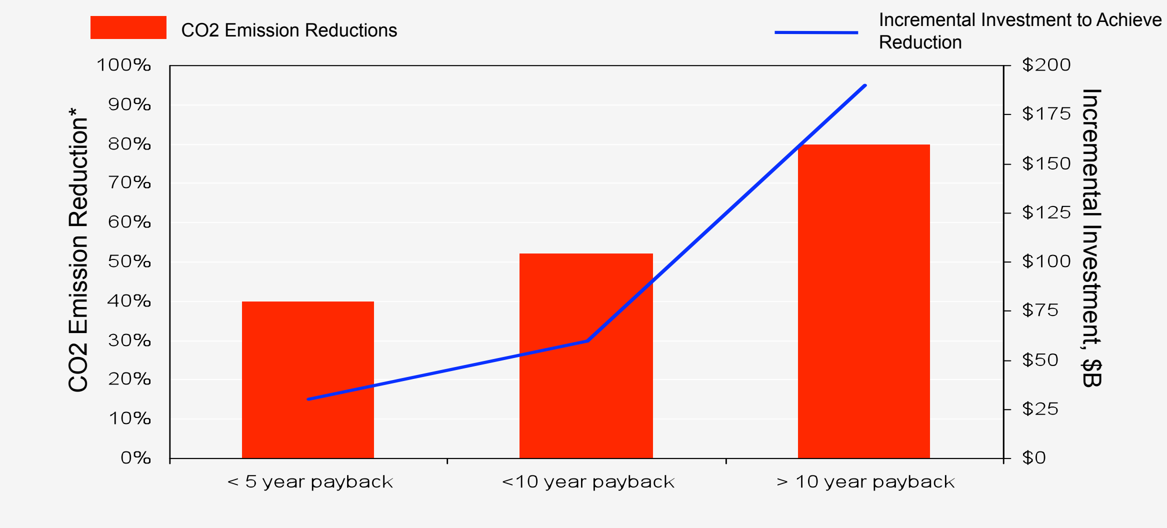
ECONOMIC ASSESSMENT – US ONLY



Auto Safety Regulations
2% First Cost Premium

Required Building Efficiency Investments
3% Total Cost Premium
13% First Cost Premium

Building Fire Safety Regulations
5% First Cost Premium



*reflects scale up of buildings contribution to IEA Blue Map scenario, 2050

RECOMMENDATIONS

Create and enforce building energy efficiency codes and labeling standards

- Extend current codes and tighten over time
- Display energy performance labels
- Conduct energy inspections and audits

Incentivize energy-efficient investments

- Establish tax incentives, subsidies and creative financial models to lower first-cost hurdles

Encourage integrated design approaches and innovations

- Improve contractual terms to promote integrated design teams
- Incentivize integrated team formation

Fund energy savings technology development programs

- Accelerate rates of efficiency improvement for energy technologies
- Improve building control systems to fully exploit energy saving opportunities

Develop workforce capacity for energy saving

- Create and prioritize training and vocational programs
- Develop “system integrator” profession

Mobilize for an energy-aware culture

- Promote behavior change and improve understanding across the sector
- Businesses and governments lead by acting on their building portfolios

Systems of Systems Approach to Energy Efficiency

Consider Buildings as Composition of Subsystems

Buildings Design Energy and Economic Analysis

Windows and Lighting

HVAC

Domestic/International Policies, Regulation, Standards, Markets

Demonstrations, Benchmarking, Operations and Maintenance

Natural Ventilation, Indoor Environment

Networks, Communications, Performance Database

Sensors, Controls, Performance Metrics

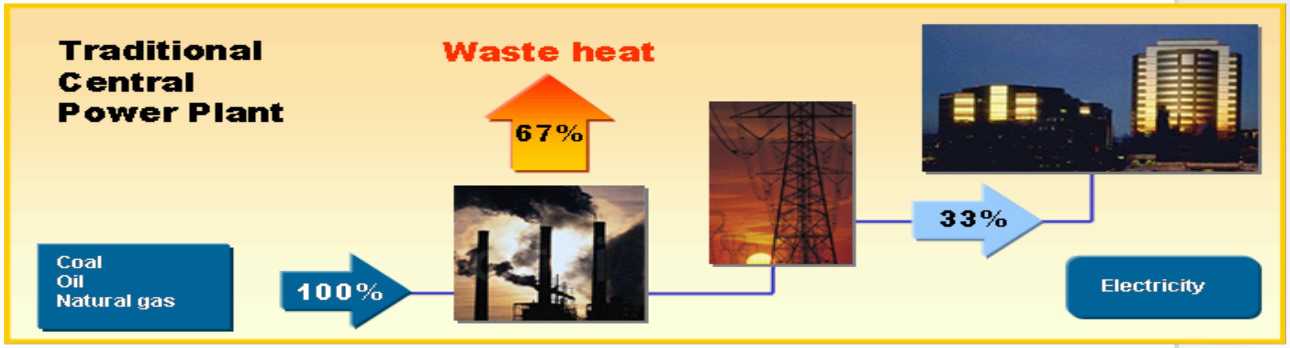
Power Delivery and Demand Response

Building Materials, Misc. Equipment

Integration: ***The Whole is Greater than the Sum of the Parts***

Combined Cooling, Heating & Power

PureComfort™ Integrated Energy Solutions



Traditional Central Power Plant

Waste heat

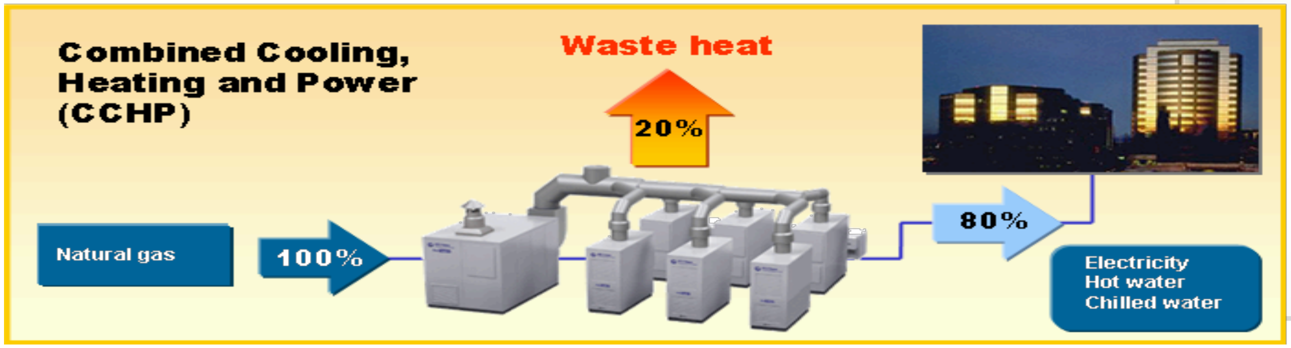
67%

Coal
Oil
Natural gas

100%

33%

Electricity



Combined Cooling, Heating and Power (CCHP)

Waste heat

20%

Natural gas

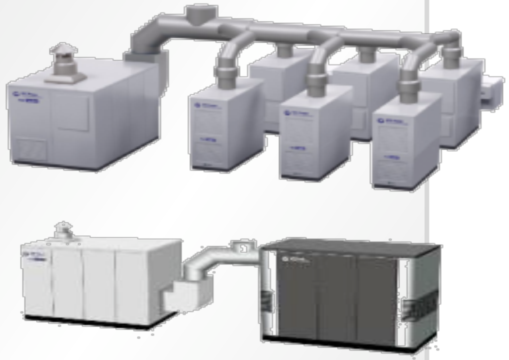
100%

80%

Electricity
Hot water
Chilled water

UTC Power

A United Technologies Company



HIGH PERFORMANCE BUILDINGS: REALITY

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

Actual energy performance lower than predictions

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

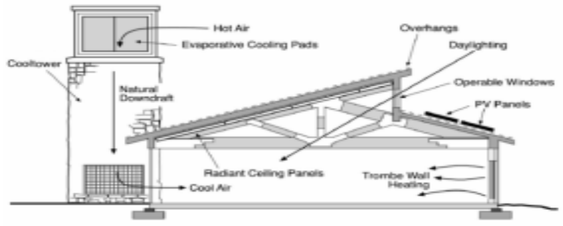


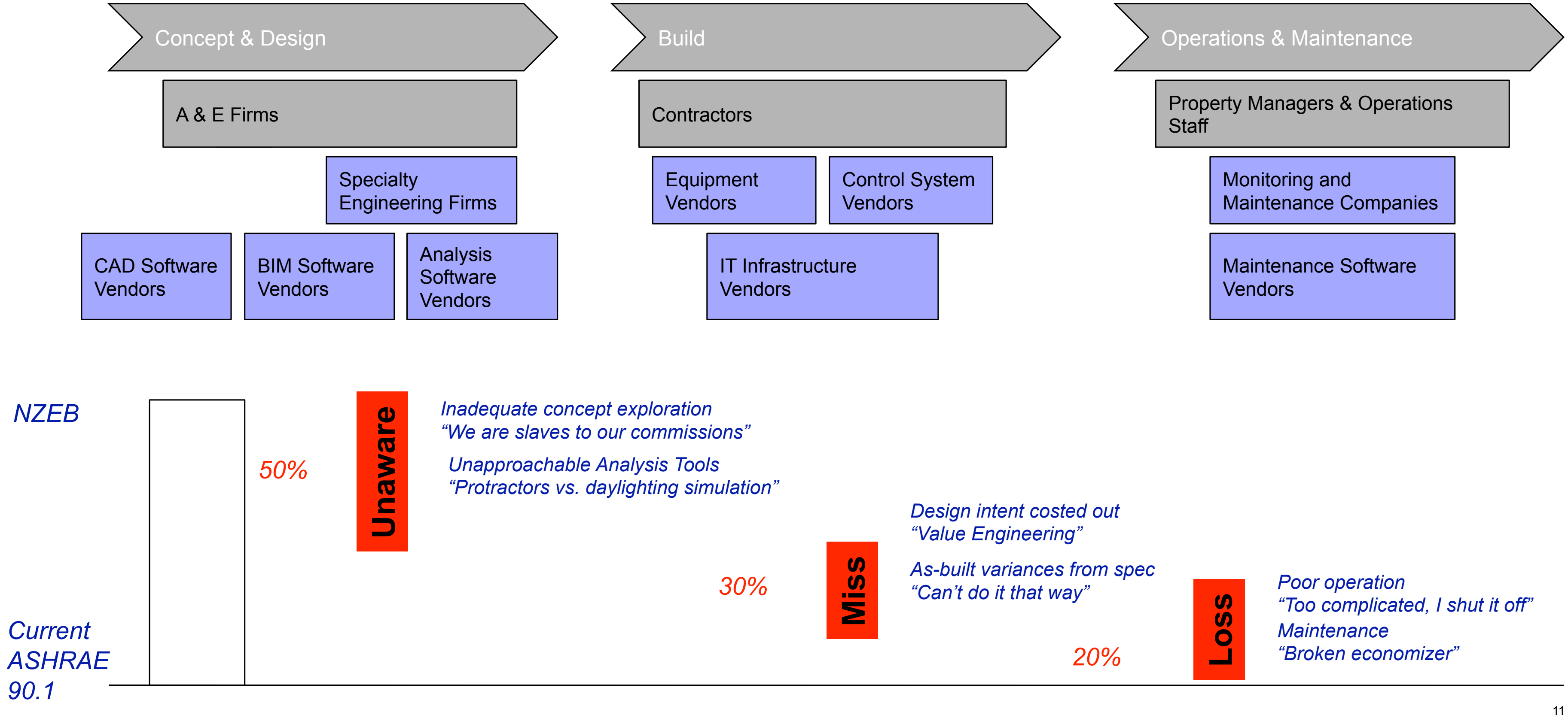
Figure 3-28 Illustration of how the cooltowers work at the Zion Visitor Center

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

Failure Modes Arising from Detrimental Sub-system Interactions

- Changes made to envelope to improve structural integrity diminished integrity of thermal envelope
- Adverse system effects due to coupling of modified sub-systems:
    - changes in orientation and increased glass on façade affects solar heat gain
    - indoor spaces relocated relative to cooling plant affects distribution system energy
- Lack of visibility of equipment status/operation, large uncertainty in loads leads to excess energy use

ENERGY IMPACT IN DESIGN-BUILD PROCESS



Concept & Design

A & E Firms

Specialty Engineering Firms

CAD Software Vendors

BIM Software Vendors

Analysis Software Vendors

Build

Contractors

Equipment Vendors

Control System Vendors

IT Infrastructure Vendors

Operations & Maintenance

Property Managers & Operations Staff

Monitoring and Maintenance Companies

Maintenance Software Vendors

Inadequate concept exploration
“We are slaves to our commissions”

Unapproachable Analysis Tools
“Protractors vs. daylighting simulation”

Design intent costed out
“Value Engineering”

As-built variances from spec
“Can’t do it that way”

Poor operation
“Too complicated, I shut it off”

Maintenance
“Broken economizer”

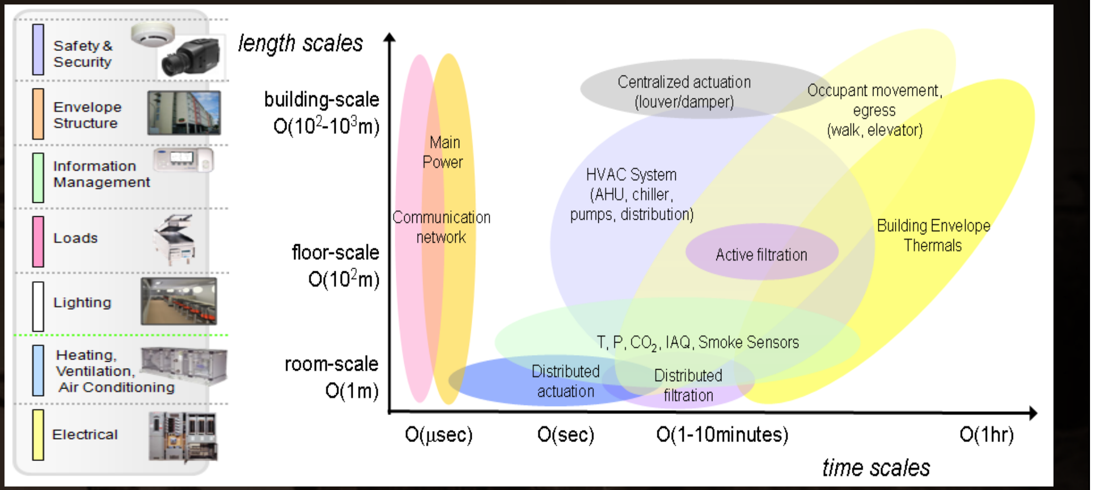
FROM R&D TO COMMERCIALIZATION

Barriers	**Enablers**
Lack of process and tools for system analysis and design	Computational science, physics-based modeling, methodology, tools and training for Integrated design
Lack of a demonstration capability for technology maturation	Full scale demonstrations facilities and concentration of talent
Lack of tools for on-going auditing, commissioning & operations	Methodology, tools and training for building operations (e.g. computational/IT/controls advances)
Lack of a long reach and broad scope in technology and business model exploration	Pre-competitive collaboration among industry, national labs and universities

Building Systems Integration Challenges

Complex* interconnections among building components

- HETEROGENEITY
  - Components do not necessarily have mathematically similar structures and may involve different scales in time or space
- SIZE
  - The number of components may be large/enormous
- DISTRIBUTED NETWORKED SYSTEMS
  - Components can be connected in a variety of ways, most often nonlinearly and/or via a network.
    Local and system wide phenomena may depend on each other in complicated ways
- FRAGMENTED MARKET
  - Long and complex value chain
  - Difficult to articulate how to attack the problem from an industrial point of view



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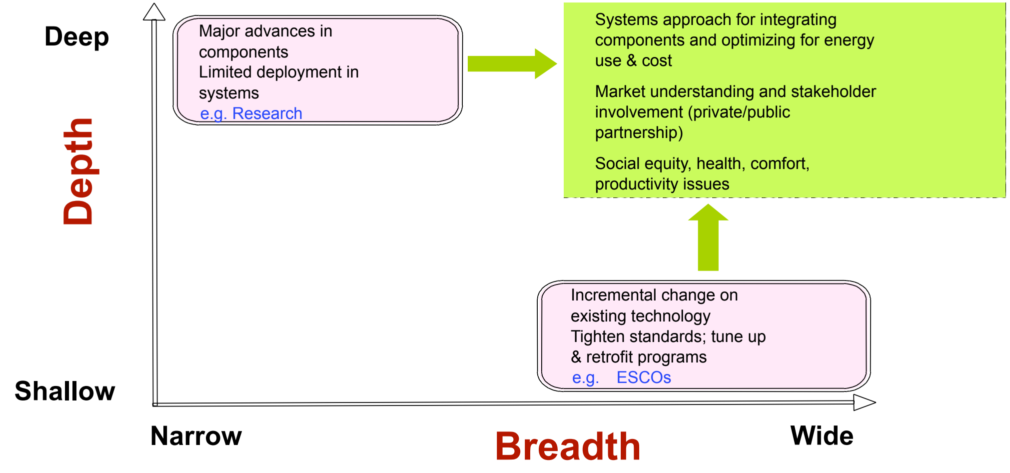
* D.L. Brown, J. Bell, D. Estep, W. Gropp, B. Hendrickson, S. Keller-McNulty, D. Keyes, J. T. Oden and L. Petzold, Applied Mathematics at the U.S. Department of Energy: Past, Present and a View to the Future, DOE Report, LLNL-TR-401536, May 2008.

Key Summary Points

- Buildings are energy intensive
- Energy consumption must decrease by 50% in all retrofits and 90% in all new buildings by 2030
  - Urgent problem
  - New construction
  - Retrofits
- Gaps in design processes
  - Modeling tools, design processes, methods to achieve the 80% universally
- Gaps in operations
  - Controls, diagnostics, robustness, “how buildings really operate”, data assimilation
- Neither has been a focus of R&D to date
  - DOE has invested in incremental improvements of existing tools, methods and process
- Barriers in policy, economics and behavior



Major advances in components
Limited deployment in systems
e.g. Research

Systems approach for integrating components and optimizing for energy use & cost

Market understanding and stakeholder involvement (private/public partnership)

Social equity, health, comfort, productivity issues

Incremental change on existing technology
Tighten standards; tune up & retrofit programs
e.g. ESCOs

- Incremental and component level research programs are unlikely to “solve” the problem, i.e. produce the changes in energy use needed.
- Problem too large to be attacked by a single entity

World-wide Landscape:
Energy Collaborative Research

Researchers at U.S. universities, led by Berkeley, **Stanford University** and the **Massachusetts Institute of Technology**, are targeting the $2 billion in energy research funds contained in the House recovery bill. The research dollars will produce jobs, reduce U.S. dependence on foreign oil and stem the production of greenhouse gases, according to the **Association of American Universities**, a group of 62 schools that conduct research.

Obama’s New Energy for America Plan, as explained on the White House Web site, calls for creating five million jobs by spending **$150 billion**, over 10 years, “to catalyze private efforts to build a clean energy future.”

Two major energy initiatives were launched in 2007: the Energy Biosciences Institute (EBI), a partnership of UC Berkeley, Berkeley Lab, and the University of Illinois, funded by BP with $500 million over ten years; and the Joint BioEnergy Institute (JBEI), a partnership of three national labs and three research universities in the San Francisco Bay Area, funded by the U.S. Department of Energy with $125 million over five years.

Example of Grand Challenges-Use Inspired Research

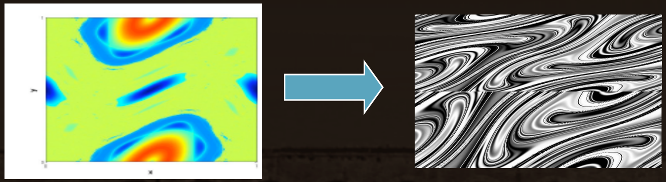
- ARPA-E is a bold concept that will provide access to the funding needed to bring the next generation of energy technologies to fruition. Specifically ARPA-E aims to:
  - Enhance our economic security by identifying technologies with the potential to reduce energy imports from foreign sources; reduce energy-related greenhouse gas emissions; and improve efficiency across the energy spectrum.
  - Ensure we remain a technological leader in developing and deploying advanced energy technologies.
- ARPA-E will uniquely focus on high risk, high payoff concepts - technologies promising true energy transformations.
- ARPA-E director: Arun Majumdar, UC Berkeley and LNBL

Barack Obama and Steven Chu addresses

Enabling Technology

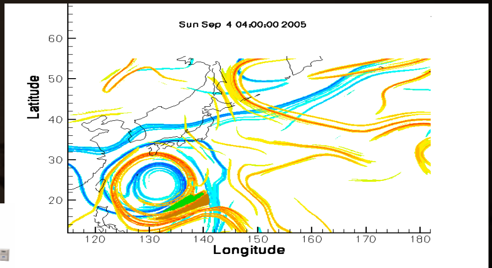
LBNL, UTRC, UC Santa Barbara, UC Berkeley, Stanford, UIUC

Safe and Immune Buildings

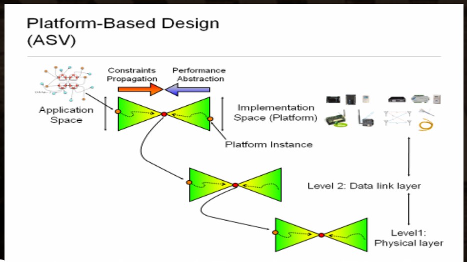


Control of Mixing

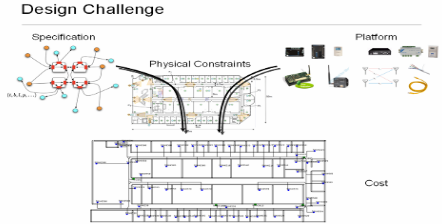
Numerical Methods for Analysis of Mixing



Net Zero Energy Buildings

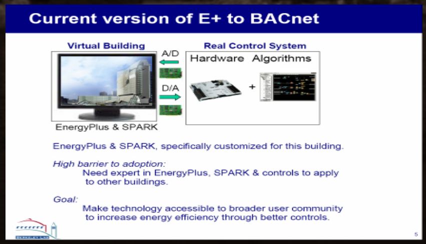


System Level Design: Platform Based Design



Building Network Synthesis: Platform Based Design

Energy Efficient Retrofits of Existing Buildings



Current version of E+ to BACnet

EnergyPlus & SPARK, specifically customized for this building.

High barrier to adoption:
Need expert in EnergyPlus, SPARK & controls to apply to other buildings.

Goal:
Make technology accessible to broader user community to increase energy efficiency through better controls.

5

Control Oriented Modeling and Design

Large-scale installations in progress….

System-level view still unclear-how is this data integrated into building operation?.

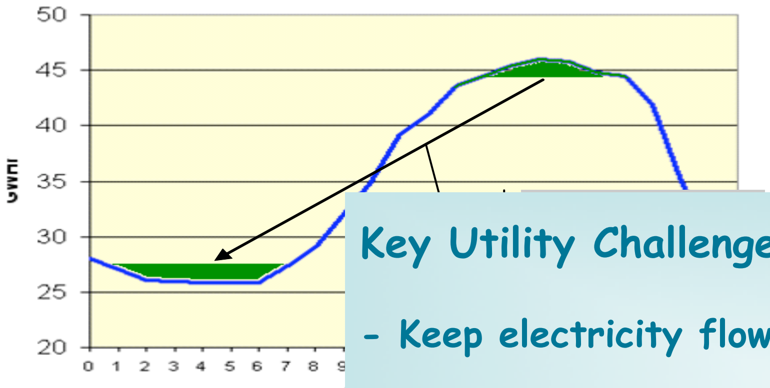
Wireless Enabled Visibility of Energy Use

Business Week: October 7th , 2009!

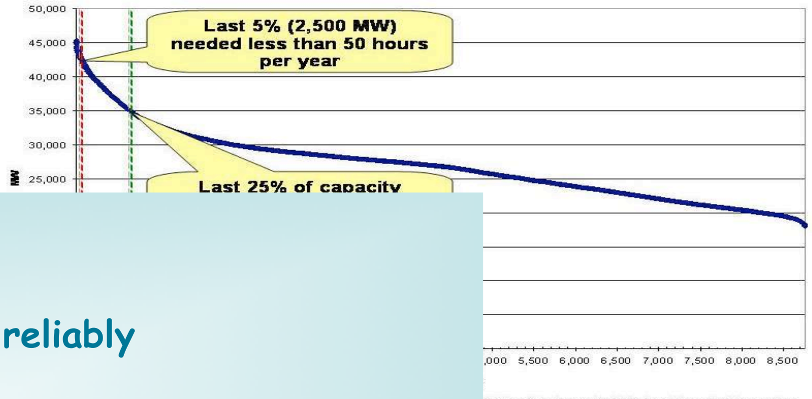
- Food producer Cargill is taking a carving knife to its electricity bills. At a plant in Springdale, Ark., where the company handles about 50,000 turkeys a day, electricity bills run more than $2 million a year. But **Cargill** thinks it can cleave $680,000 from the total by using its own generators on high-demand days. The secret behind this money-saving plan lies in what's known as the **smart grid**—a wholesale revamp of the system that distributes energy to homes and businesses around the country. Government bodies and utility providers are in the early stages of this multibillion-dollar upgrade to transform the existing grid into **a two-way network where power and information flow in both directions between the utility and the customer,** not just from the provider to the user.
- The Electric Power Research Institute, a nonprofit research and design group, estimates that it will **cost $165 billion, or roughly $8 billion a year for 20 years**, to create the smart grid. The market for the gear needed to overhaul smart-grid communications alone may reach **$20 billion a year in five years**, Cisco estimates. Other technology companies developing smart-grid software and hardware include IBM, Oracle, Google, and Siemens.

Challenges for the 21st Century Utility

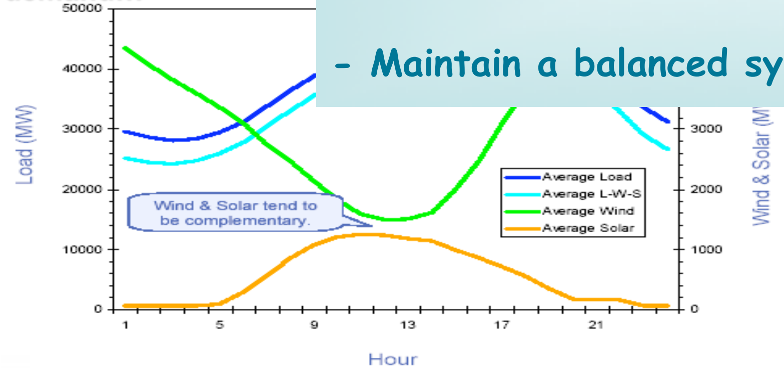
Peak Load is 2x greater than off-peak…

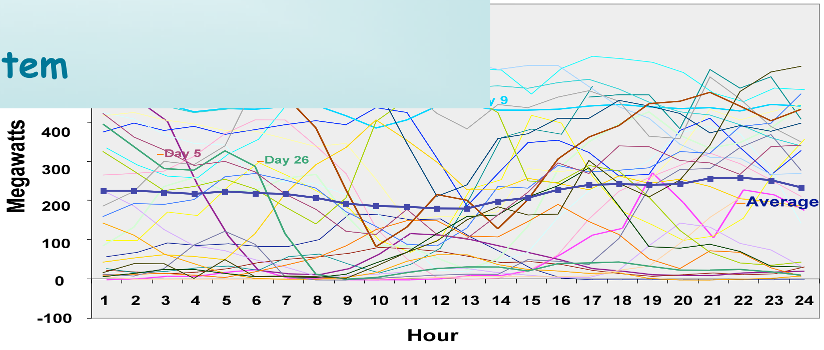


…leading to significant unutilized capacity



Wind and solar are non
demand…



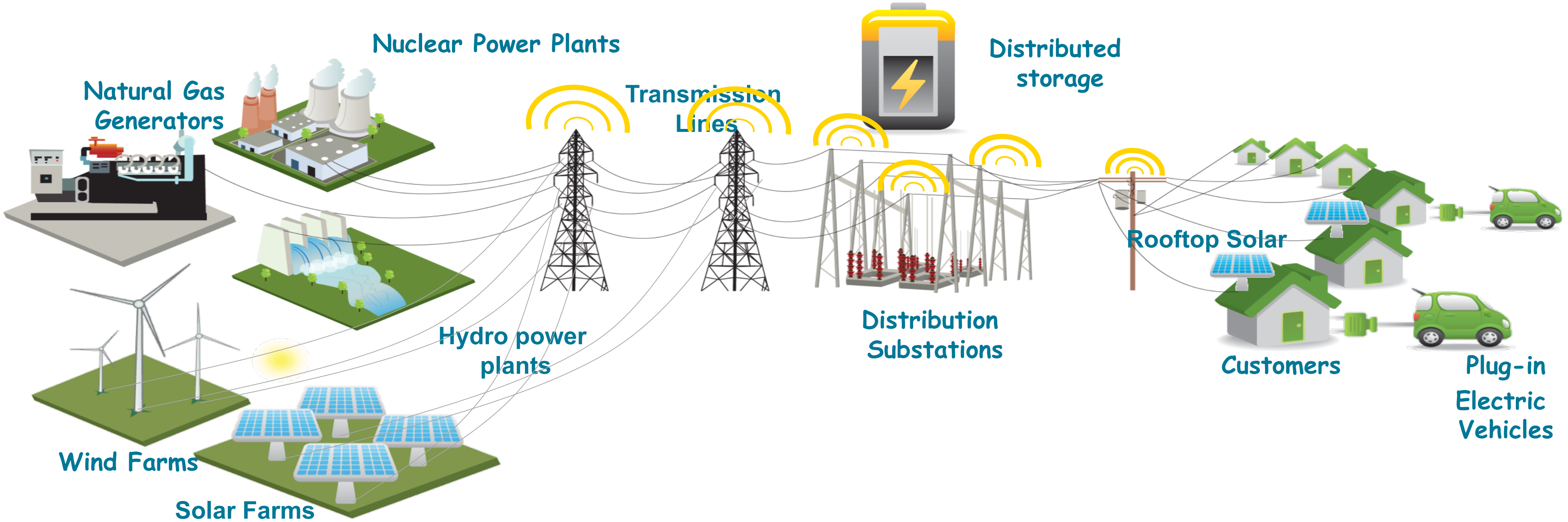


Key Utility Challenges:

- Keep electricity flowing reliably
- Integrate increasing amounts of distributed and intermittent resources
- Maintain a balanced system

Large-scale Renewables and Distributed Resources Impact Supply and Demand Unpredictably…

… Driving the Need for a Smarter Grid



A Smart Grid

Smart

Overlay with an "Intelligent" Infrastructure

- Pervasive sensing and measurement devices
- Pervasive control devices
- Advanced data communications
- Computing and information management

Power Plants

Transmission Networks

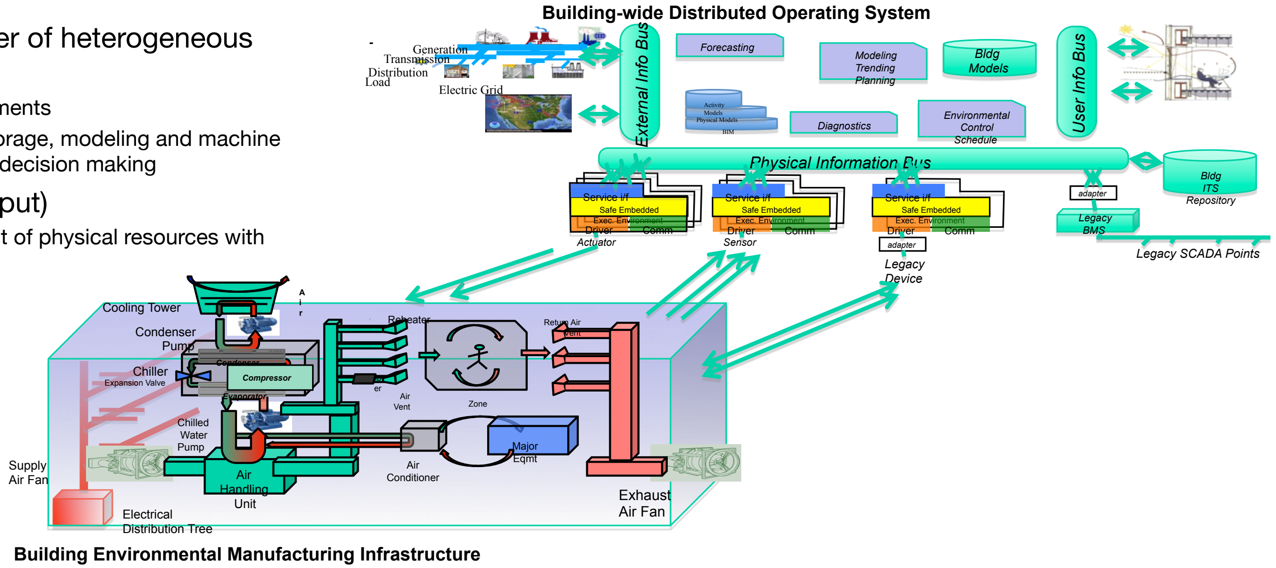
Substations

Distribution Networks

Consumers

Towards a Building-wide Integrated Operating System

- ❖Model-driven
  - ❖First principle, physics-based
  - ❖Data-driven, feature-based
- ❖Integration of large number of heterogeneous sensors and actuators
  - ❖Sensor, Information-rich environments
  - ❖Discovery, tasking, collection, storage, modeling and machine learning, visualization, on/offline decision making
- ❖Policy expression (user input)
  - ❖Interpretation and management of physical resources with respect to high-level policies
- ❖Security and privacy
  - ❖Fault-detection
  - ❖Isolation
  - ❖Recovery



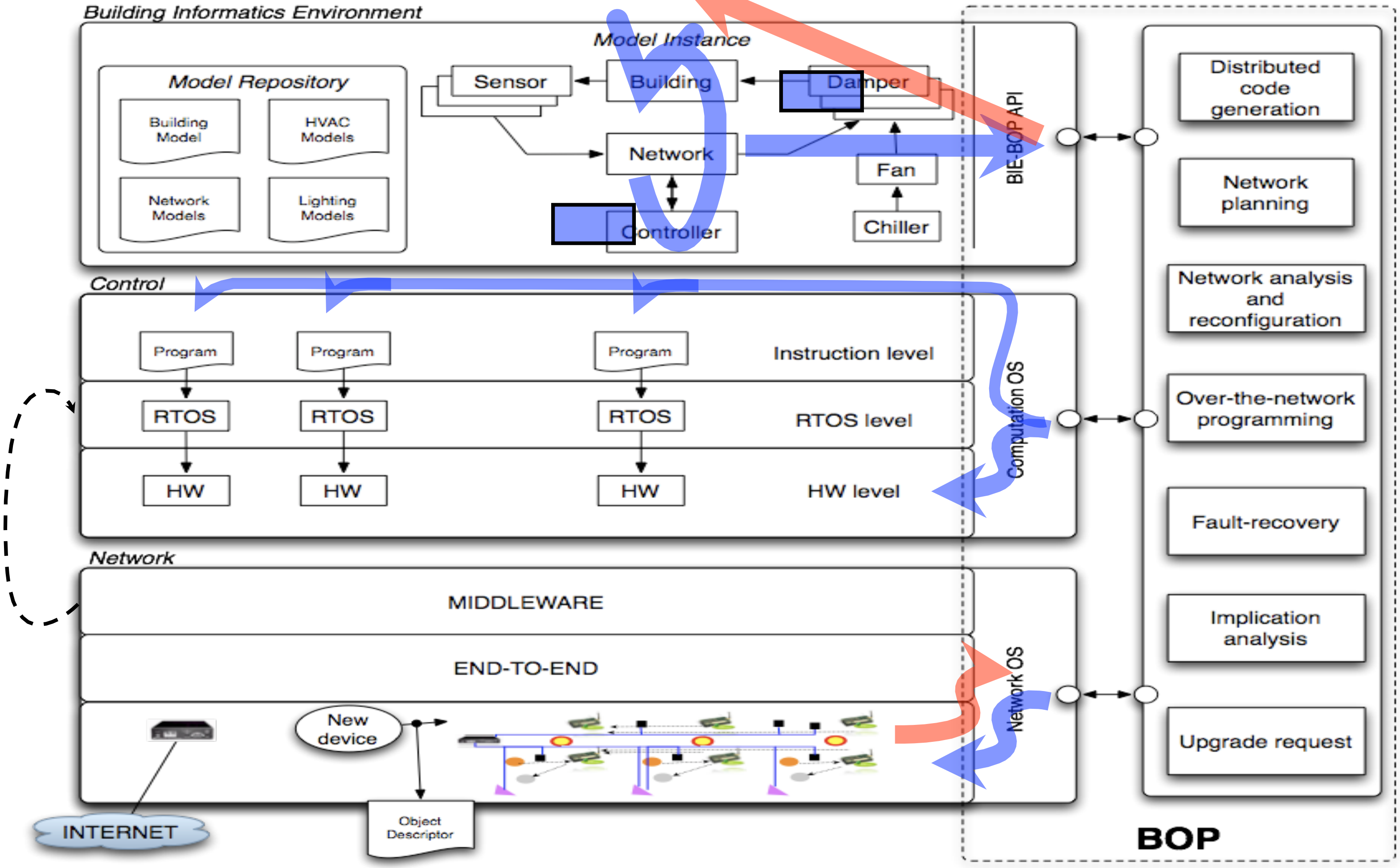
Building-wide Distributed Operating System

Building Environmental Manufacturing Infrastructure

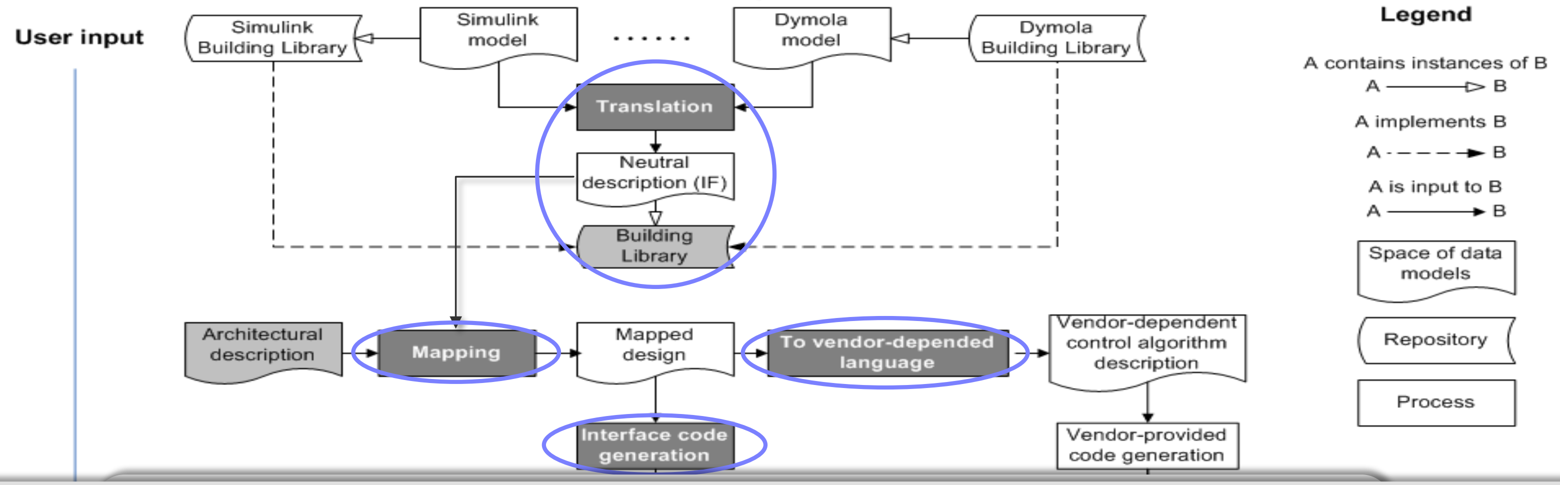
- ❖Static, model-driven commissioning
- ❖Building Management Systems (BMS)
- ❖Set-point driven control scheme
  - ❖Temperature, pressure, flow rates, motor speeds, louver positions
- ❖Set-points maintained at control points
- ❖Forgoes closed-loop feedback and dynamic modeling
  - ❖Building viewed as fixed structure

- ❖Individual building as part of larger Grid network
  - ❖IPSes inside building
  - ❖External negotiation for power through IPS
- ❖BIOS/IPS integration
  - ❖Management of user policies and IPS policies
  - ❖Load shifting/shedding working in concert with grid

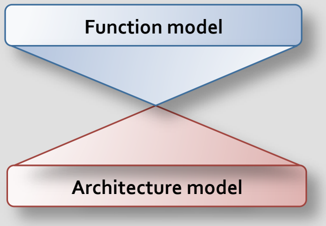
Building Operating Platform



Software Synthesis Flow



Mapping and Communication Interface



Objective

- Minimize life-cycle cost

Constraints

- End-to-End latency constraints
- Utilization constraints

Variables

- Allocation of tasks to processing units
- Allocation of messages
- Assignment of priorities to tasks and messages
- Assignment of periods to tasks

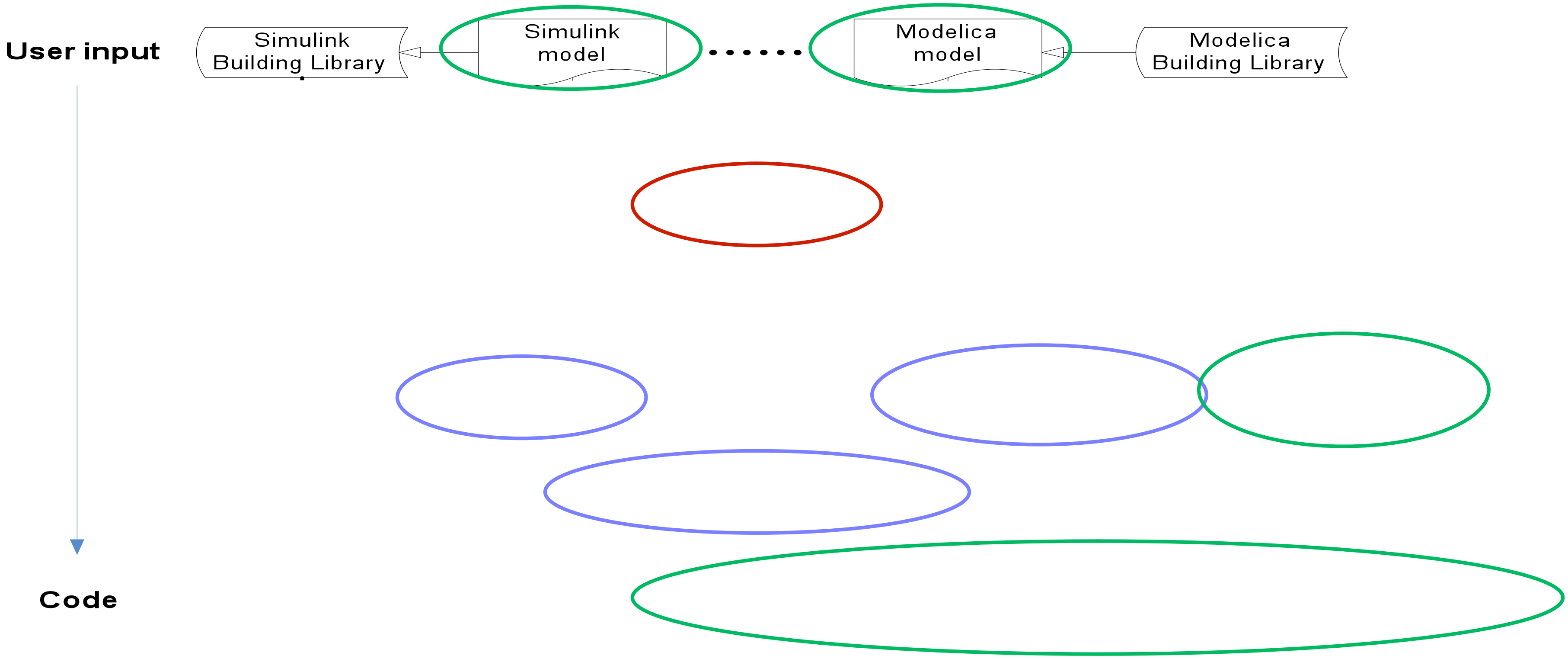
To maintain behavior when distributing the system

- Stream equivalence:

  Communication between tasks guarantee no loss of data, so that values of the data are kept the same as the original system.

  - Protocols to guarantee stream equivalence on LTTA *[Benveniste et.al, "Loosely Time-Triggered Architectures based on Commnication-by-Sampling", 2007]*
  - Application example: historical data storage.
- Real-time data:
  - Also guarantee the timeliness of data.
  - Add latency constraints according to time assumption in the functional model and resolve them.
  - Application example: real-time control systems such as HVAC and lighting control.

Software Synthesis Flow



User input

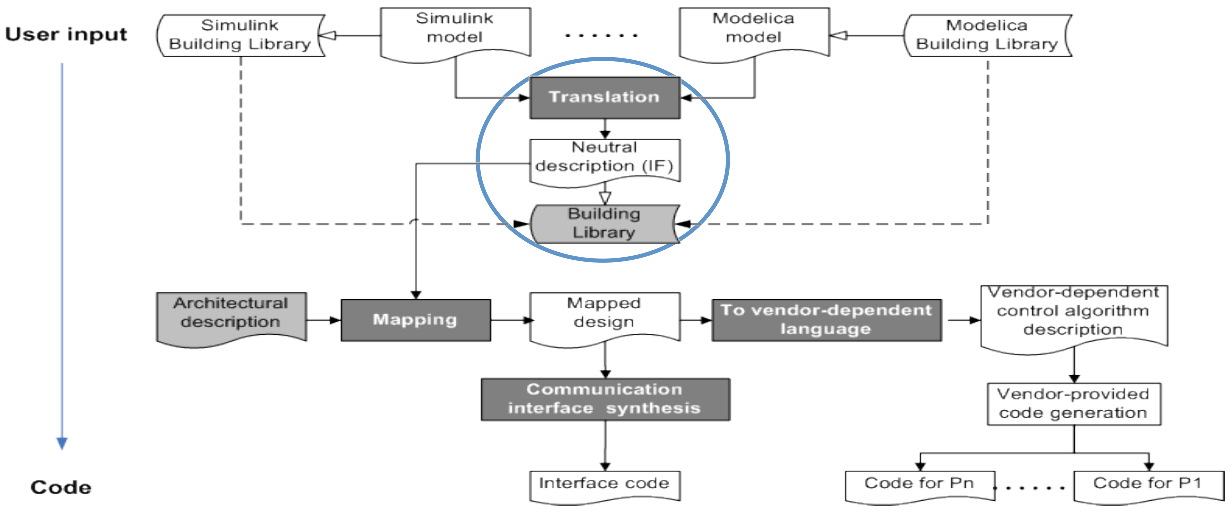
Simulink
Building Library

Simulink
model

Modelica
model

Modelica
Building Library

Code



User input

Simulink Building Library

Simulink model

. . . . . .

Modelica model

Modelica Building Library

Translation

Neutral description (IF)

Building Library

Architectural description

Mapping

Mapped design

To vendor-dependent language

Vendor-dependent control algorithm description

Communication interface synthesis

Vendor-provided code generation

Code

Interface code

Code for Pn

. . . . .

Code for P1

INTERCHANGE FORMAT

Interchange Format (IF)

- What is IF

  A file, or a set of files, which contains data in a given syntax that is understood by different interacting tools. [A. Pinto, "Interchange Formats for Hybrid Systems: Review and Proposal", *Hybrid Systems: Computation and Control*, 2005.]

- Motivation
  - Linear number of translators versus quadratic number of translators.
  - One mapping framework on IF models versus different mapping frameworks for different modeling languages .

- We need IF that
  - support hybrid, heterogeneous, and hierarchical models
  - preserve semantics during translations
  - support mapping from IF to architecture models

Hybrid System

- The system has a continuous evolution and occasional jumps.
- Definition: [J. Lygeros PHD thesis]

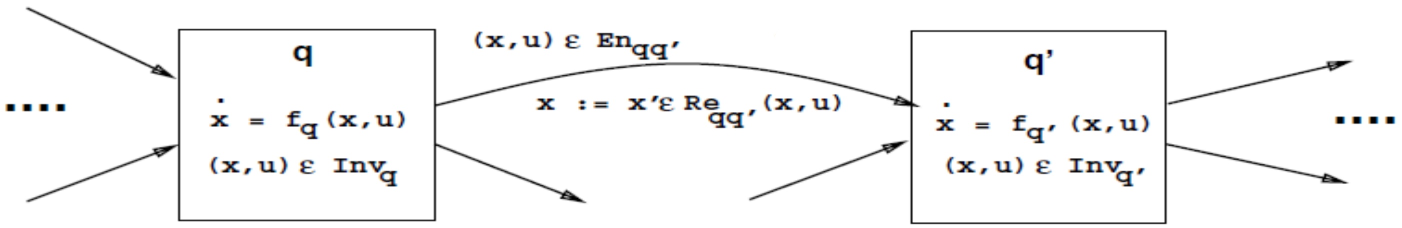
state, input, and output spaces

initial states

A Hybrid System $$H = (X, U, Y, I, f, E, h)$$

continuous evolution
$f : X \times U \to TX_c$

state transition and output evolution
$E \subset X \times U \times X$ $h : X \times U \to Y$



Interchange Format in Our Design Flow

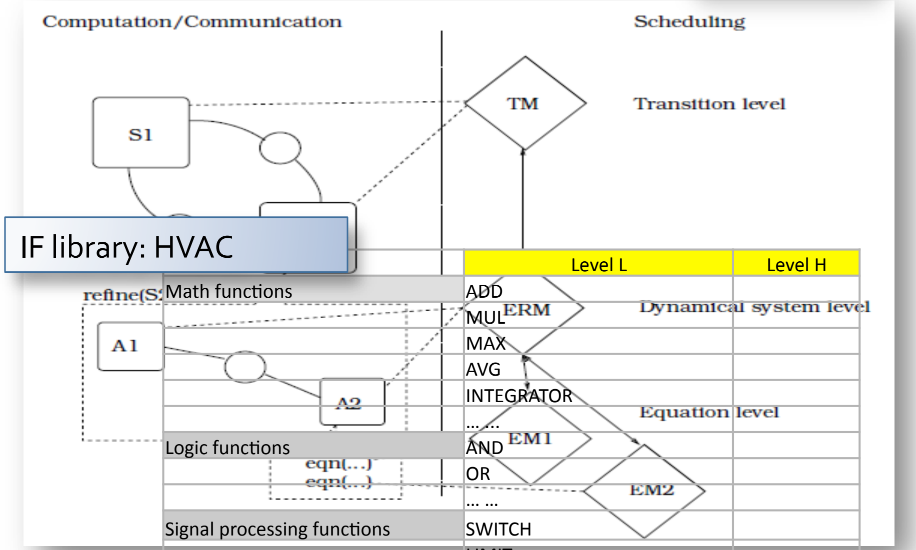
Details

- MMM-based IF

  [A. Pinto, "Interchange Formats for Hybrid Systems: Review and Proposal", *Hybrid Systems: Computation and Control*, 2005]
  - A netlist with 3 basic components

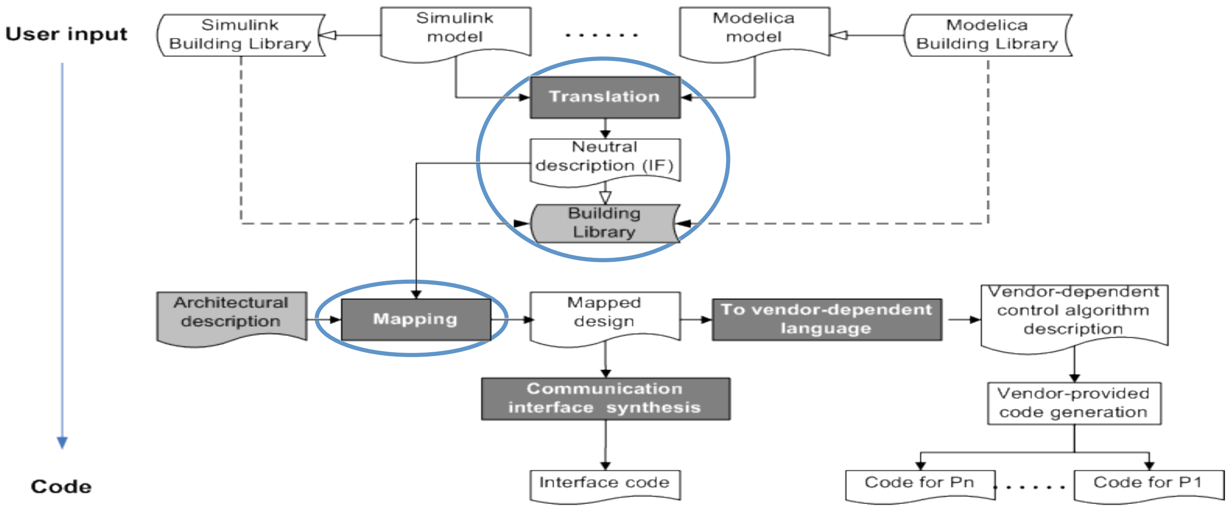
    processes, media, quantity managers
  - Special components added for hybrid systems.
- Our extension
  - Domain specific IF library
    - make translation faster
    - correct-by-construction
    - pre-characterized components for mapping
    - different abstraction levels for accuracy and complexity tradeoff
  - Leverage Metropolis framework for
    - validation of IF models

      (dynamic validation or formal verification)
    - mapping of IF models



IF library: HVAC

	Level L	Level H
Math functions	ADD	
	MUL	
	MAX	
	AVG	
	INTEGRATOR	
	… …	
Logic functions	AND	
	OR	
	… …	
Signal processing functions	SWITCH	
	LIMIT	
	SPAN	
	… …	
Control functions		PID
		SETPOINT
		… …
Time functions	OCCUPANCY SCHEDULE	
	TIMER	
	… …	
Psychrometric fuctions	ENRH	
	WBRH	
	… …	



User input

Simulink Building Library

Simulink model

. . . . . .

Modelica model

Modelica Building Library

Translation

Neutral description (IF)

Building Library

Architectural description

Mapping

Mapped design

To vendor-dependent language

Vendor-dependent control algorithm description

Communication interface synthesis

Vendor-provided code generation

Code

Interface code

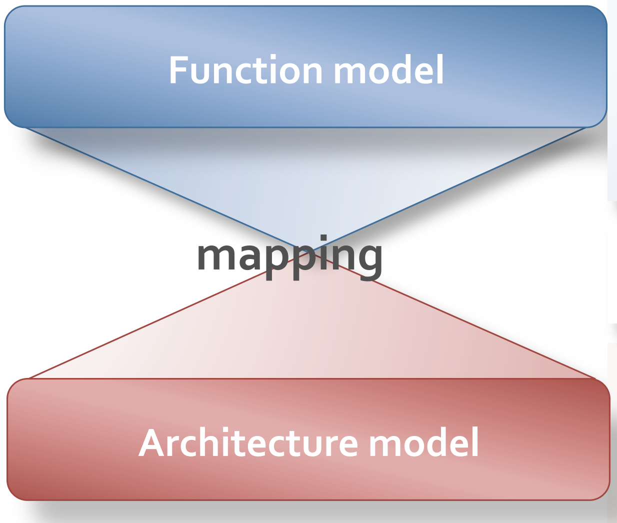
Code for Pn

. . . . .

Code for P1

MAPPING

Mapping for Building Control Systems



Formulated from MMM-based IF

❖Computation/communication netlist

process → task
medium → message

❖ Scheduling netlist

scheduling constraints

❖Objective function and constraints

cost, extensibility, latency, utilization

❖Distributed

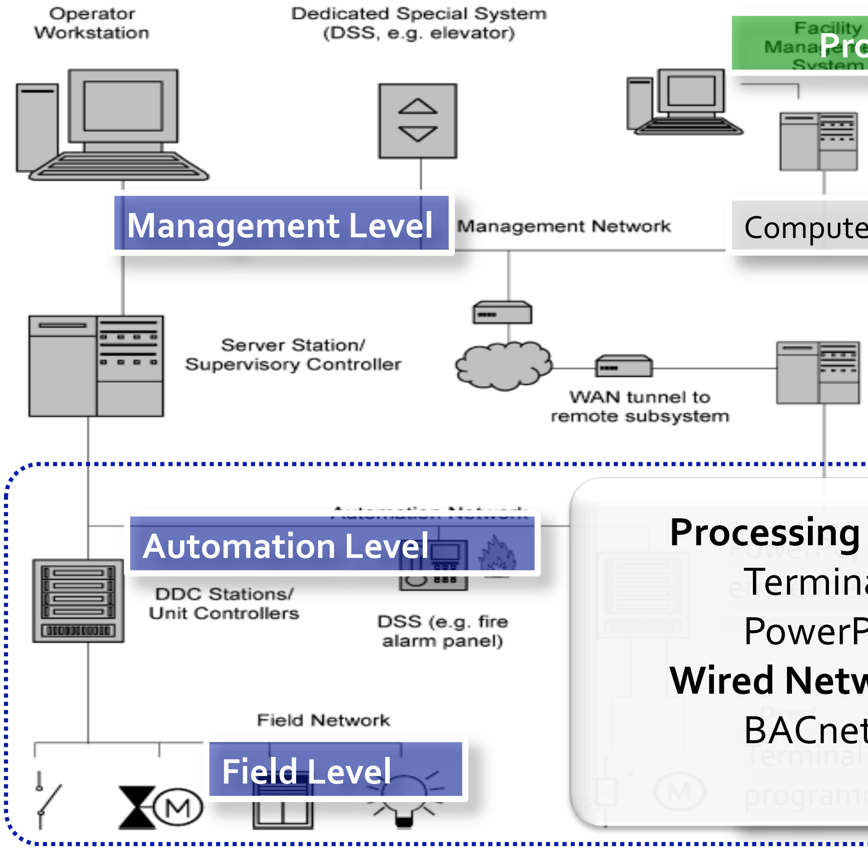
❖Asynchronous

sensor, actuator, processors
with local clocks (drift and jitter)

- BACnet based systems
  (building control applications)
- CAN-bus based systems
  (automotive & avionics applications)

More Details

Building Control System Hierarchy



Management Level

Automation Level

Field Level

Processing Units

Computer workstation

Network

Throughput

High-performance network backbone (e.g. IT network)

Timeliness

Cost efficient local control networks (e.g. independent network each floor, with CSMA variants supporting prioritization)

Terminal Unit controller (pre-programmed)

Processing Units:

Terminal Unit Controller

PowerPC with QNX RTOS

Wired Network:

BACnet/LonTalk

Problem Statement

Mapping problem of building control systems (automation and field levels)

Objective

- Minimize life-cycle cost

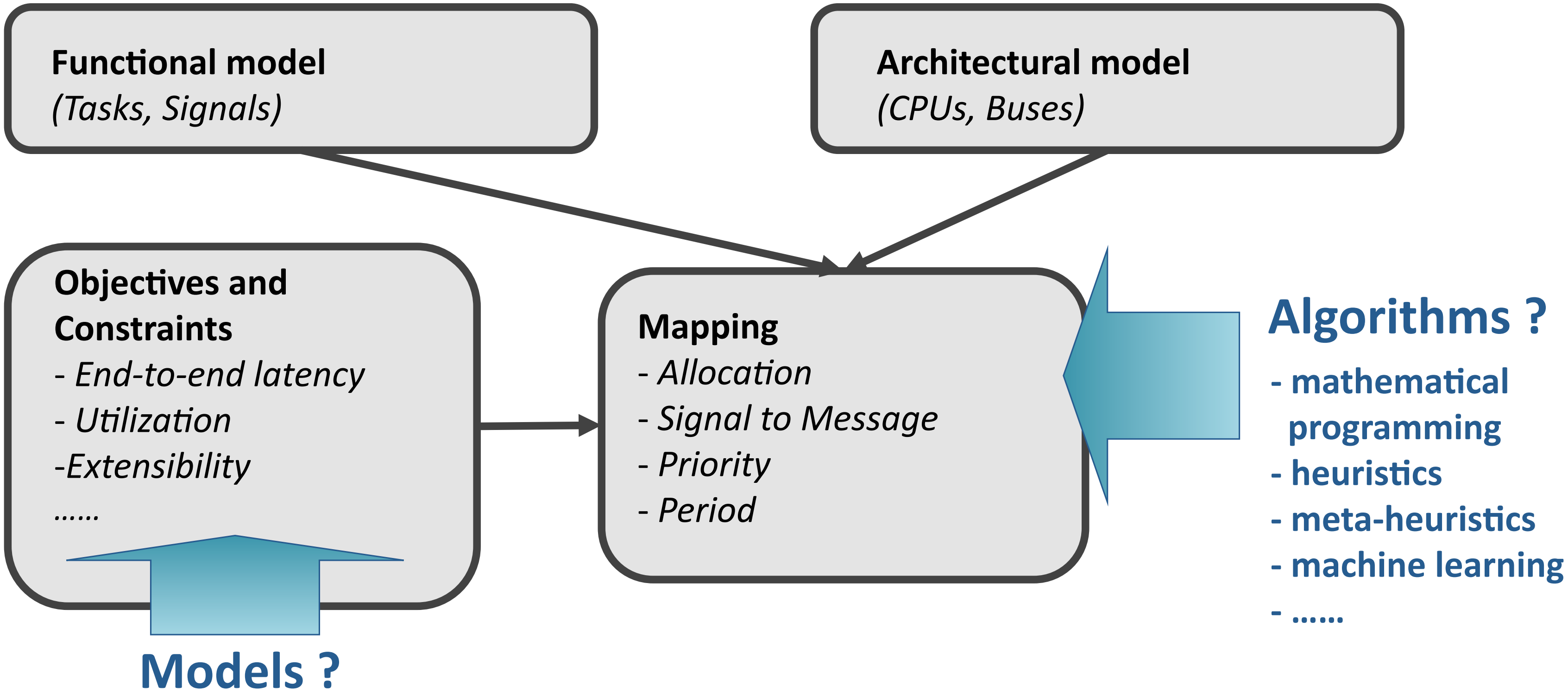
Constraints

- End-to-End latency constraints
- Utilization constraints

Variables

- Allocation of tasks to processors
- Assignment of priorities and CPU budgets to tasks
- Allocation of messages to communication paths
- Assignment of priorities to messages
- Task periods

Mapping for Real-time Systems



Functional model
(Tasks, Signals)

Architectural model
(CPUs, Buses)

Objectives and Constraints
- *End-to-end latency*
- *Utilization*
-*Extensibility*
……

Mapping
- *Allocation*
- *Signal to Message*
- *Priority*
- *Period*

Algorithms ?
- **mathematical programming**
- **heuristics**
- **meta-heuristics**
- **machine learning**
- **……**

Models ?

General Problem Formulation

- Symbols:
    - Function primitive instances : $F = (f_1, f_2, \ldots, f_n)$
    - Architecture primitive instances : $A = (a_1, a_2, \ldots, a_m)$
    - Mapping decision variables : d_{ij}
    - Quantities (power, area, bandwidth…): Q_{ijk}^l
- Constraints:
    - Decision constraints: $\sum_{j \in S_i} d_{ij} = 1 \quad \forall i, \; 1 \le i \le n$
        - Each function primitive instance needs to be <u>covered</u> by one and only one architecture primitive instance.
    - Quantity constraints: $H_t^l(d_{ij}, Q_{ijk}^l) \le QC_t^l$
        - Constraints from architecture platform or design constraints, such as power constraints, bandwidth constraints, etc.
- Objective function:
    - Cost function: $G_l(d_{ij}, Q_{ijk}^l)$

General Formulation for Building Control

- Optimization variables

a_{τ_i,p_j},	a_{m_i,r_j},	π_{τ_i},	b_{τ_i},	π_{m_i},	t_{τ_i}
task allocation	message allocation	task priority	task budget	message priority	task period

- Problem Formulation
  - Allocation constraints

$$\sum_{p_j} a_{\tau_i,p_j} = 1 \quad \forall \tau_i$$

$$\sum_{r_j} a_{m_i,r_j} = 1 \quad \forall m_i$$

$$a_{\tau_i,p_u} \wedge a_{\tau_j,p_v} \longrightarrow \sum_{r_w \in r(p_u,p_v)} a_{m_k,r_w} = 1 \quad m_k \in m(\tau_i,\tau_j)$$

  - CPU budget constraints

$$\sum_{\tau_i} a_{\tau_i,p_j} b_{\tau_i} = 1 \quad \forall p_j$$

- E2E latency constraints

$$\sum_{\tau_i \in \rho_j} l_{\tau_i} + \sum_{m_i \in \rho_j} l_{m_i} \leq L_{\rho_j} \qquad \forall \rho_j$$

$$a_{\tau_i,p_j} \rightarrow (c_{\tau_i} = C_{\tau_i,p_j}) \qquad (a_{m_i,r_j} \wedge r_j[h_k]) \rightarrow (c_{m_i}[h_k] = C_{m_i,h_k})$$

- Utilization constraints

$$m_{p_j} = \sum_{\tau_i} a_{\tau_i,p_j} M_{\tau_i,p_j} \leq K^M_{p_j}, \quad c_{p_j} = \sum_{\tau_i} a_{\tau_i,p_j} C_{\tau_i,p_j} \leq K^C_{p_j}, \quad \forall p_j$$

$$c_{h_k} = \sum_{m_i} c_{m_i}[h_k] \leq K^T_{h_k}, \qquad \forall h_k$$

- Cost optimization

$$\min\ f_{\text{cost}}(u_{p_j}, u_{c_k})$$

$$a_{\tau_i,p_j} \rightarrow u_{p_j} \qquad (a_{m_i,r_j} \wedge r_j[h_k]) \rightarrow u_{h_k}$$

MIGP

MILP

PB

Computation Node with QNX RTOS

- QNX RTOS uses Adaptive Partition Scheduling (APS) algorithm:
  - Behavior under normal load: a priority-driven pre-emptive scheduler.
  - Behavior under overload: a fair-share thread scheduler which guarantees a user-specified percentage of CPU time to each group of threads.
  - Borrowed time: critical thread runs even without budget.
  - A sliding window (100ms) to keep history of CPU usage of tasks.

Computation Latency

- **Task computation latency**

$$l_{\tau_i} = \underset{\substack{\nearrow \\ \text{period}}}{t_{\tau_i}} + \underset{\substack{\nwarrow \\ \text{response time}}}{r_{\tau_i}}$$

- **Field level**

  Terminal Unit controller (e.g. zone controller ZN253 from ALC, Trend IQLVAV)

  Response time $$r_{\tau_i} = c_{\tau_i} \xleftarrow{} \text{computation time}$$

- **Automation level**

  More powerful processors (PPC with **QNX RTOS**)
  - support multitasking

  Response time $$r_{\tau_i} = c_{\tau_i} + scheduling\ delay$$

  - Critical task worst-case response time $r_{\tau_i} = c_{\tau_i}$

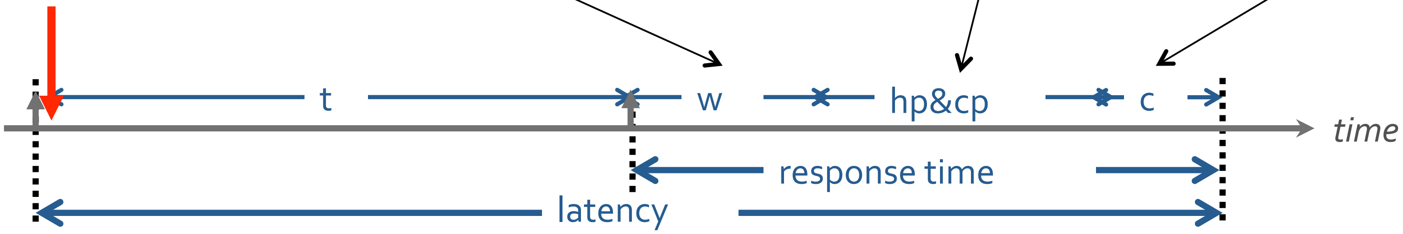
Computation Latency Contd.

- **Automation level**
  - Non-critical task worst-case latency illustration

blocked because out of budget

blocked/preempted by higher priority tasks

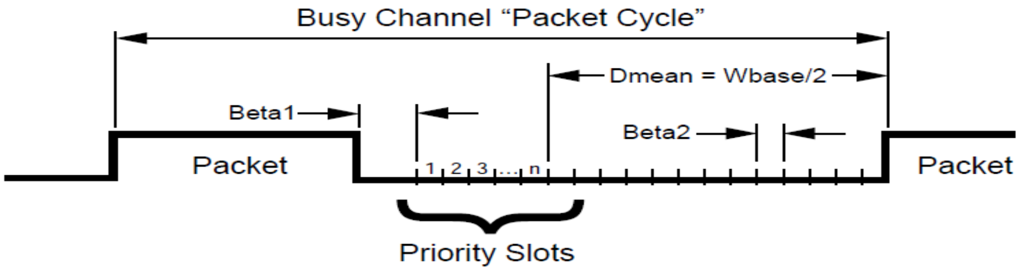
computation time



$$r_{\tau_i} = \underbrace{\max\{0.1(1-b_{\tau_i}) - t_{\tau_i}, 0\}}_{\text{blocked because out of budget}} + \underbrace{\sum_{\tau_j \in hp(\tau_i)} \min\left\{\left\lceil \frac{r_{\tau_i}}{t_{\tau_j}} \right\rceil c_{\tau_j}, r_{\tau_i} b_{\tau_j}\right\}}_{\text{blocked/preempted by higher priority tasks}} + \underbrace{\sum_{\tau_j \in cp(\tau_i)} \left\lceil \frac{r_{\tau_i}}{t_{\tau_j}} \right\rceil c_{\tau_j}}_{\text{blocked/preempted by critical tasks}} + c_{\tau_i}$$

Communication Protocol - LonTalk

- Predictive p-persistent CSMA protocol



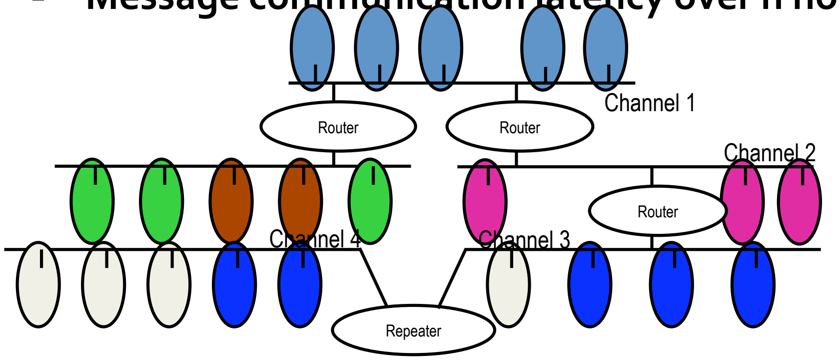
  - Node continues monitoring the channel until it detects no transmission during β1.
  - Node delays a random backoff.
  - Transmits if the channel is still idle after the delay expires, s.
  - Otherwise, competes for the channel access again.
  - Resend messages if collision occurs.
  - Optional priority slots for priority messages.
  - Optional collision detection and resending.

Communication Latency of BACnet/LonTalk

- **Response time**
  - Priority message worst-case response time

$$r_{m_i} = \overbrace{\max_{m_j \in lp(m_i)} \{c_{m_j}\}}^{\text{blocked by a lower priority message}} + \underbrace{\sum_{m_j \in hp(m_i)} \left\lceil \frac{r_{m_i} - c_{m_i}}{t_{m_j}} \right\rceil c_{m_j}}_{\text{blocked by higher priority messages}} + \overbrace{c_{m_i}}^{\text{transmission time}}$$

- **Message communication latency over n hops**



$$l_{m_i} = \sum_{k=1}^{n} r_{m_i}(channel_k)$$

Problem Formulation for QNX RTOS + LonTalk (in MIGP)

- Optimization variables

a_{τ_i,p_j},	a_{m_i,r_j},	$\pi_{\tau_i,\tau_j}, \pi'_{\tau_i}$,	b_{τ_i},	π_{m_i,m_j}	t_{τ_i}
task allocation	message allocation	task priority	task budget	message priority	task period

- Problem Formulation
  - Allocation constraints

$$\sum_{p_j} a_{\tau_i,p_j} = 1 \quad \forall \tau_i \qquad \sum_{r_j} a_{m_i,r_j} = 1 \quad \forall m_i$$

$$\sum_{r_w \in r(p_u,p_v)} a_{m_k,r_w} - a_{\tau_i,p_u} - a_{\tau_j,p_v} \geq -1 \quad \forall m_k \in m(\tau_i,\tau_j), \forall \tau_i \neq \tau_j, \forall P_u \neq P_v$$

  - Budget assignment constraints

$$\sum_{\tau_i} a_{\tau_i,p_j} b_{\tau_i} = 1 \quad \forall p_j$$

  - Assignment to Additional variables

$$a_{\tau_i,\tau_j} = \sum_{p_k} a_{\tau_i,p_k} a_{\tau_j,p_k} \qquad a_{m_i,m_j}[h_k] = a_{m_i,h_k} a_{m_j,h_k} \qquad a_{m_i,h_k} = \sum_{r_j} a_{m_i,r_j} r_j[h_k]$$

$$c_{\tau_i} = \sum_{p_j} a_{\tau_i,p_j} C_{\tau_i,p_j}, \quad u_{p_j} = \sum_{p_j} a_{\tau_i,p_j}$$

$$(c_{m_i}[h_k] = a_{m_i,h_k} C_{m_i,h_k}, \quad u_{h_k} = \sum_{m_i} a_{m_i,h_k}$$

- End-to-End latency constraints

$$\sum_{\tau_i \in \rho_j} l_{\tau_i} + \sum_{m_i \in \rho_j} l_{m_i} \le L_{\rho_j} \qquad \forall \rho_j$$

$$l_{\tau_i} = t_{\tau_i} + r_{\tau_i}, \quad l_{m_i} = r_{m_i}$$

$$r_{\tau_i} = \pi_{\tau_i} c_{\tau_i} + (1 - \pi_{\tau_i})(w_{\tau_i} + \sum_{\tau_j} a_{\tau_i,\tau_j} \pi_{\tau_j,\tau_i} \alpha_{\tau_i,\tau_j} + \sum_{\tau_j} a_{\tau_i,\tau_j} \pi'_{\tau_j} \lambda_{\tau_j,\tau_i} c_{\tau_j} + c_{\tau_i})$$

$$r_{m_i} = \sum_{h_k} r_{m_i}[h_k] = B_{\max}[h_k] + \sum_{m_j} a_{m_i,m_j}[h_k] \pi_{m_j,m_i} \lambda_{m_i,m_j}[h_k] c_{m_j}[h_k] + c_{m_i}[h_k]$$

$$w_{\tau_i} \ge 0, \quad w_{\tau_i} \ge 0.1 - 0.1 b_{\tau_i} - t_{\tau_i},$$

$$\lambda_{\tau_j,\tau_i} t_{\tau_j} \ge r_{\tau_i} \qquad \alpha_{\tau_i,\tau_j} \le \lambda_{\tau_i,\tau_j} c_{\tau_j}, \quad \alpha_{\tau_j,\tau_i} \le r_{\tau_i} b_{\tau_i},$$

$$B_{\max}[h_k] \ge a_{m_i,m_j}[h_k] \pi_{m_i,m_j} c_{m_j}[h_k]$$

$$\lambda_{m_i,m_j}[h_k] \ge (r_{m_i}[h_k] - c_{m_i}[h_k]) / t_{m_j}$$

- Utilization constraints

$$m_{p_j} = \sum_{\tau_i} a_{\tau_i,p_j} M_{\tau_i,p_j} \le K^{M}_{p_j}, \quad c_{p_j} = \sum_{\tau_i} a_{\tau_i,p_j} C_{\tau_i,p_j} \le K^{C}_{p_j}, \quad \forall p_j$$

$$c_{h_k} = \sum_{m_i} c_{m_i}[h_k] \le K^{T}_{h_k}, \qquad \forall h_k$$

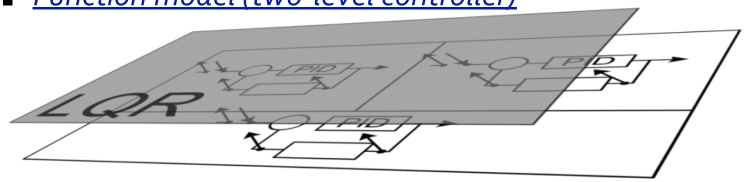
- Cost Optimization

$$\min \sum_{p_j} \$_{p_j} u_{p_j} + \sum_{c_k} \$_{c_k} u_{c_k} - \sum_{\tau_j \ne \tau_i} \alpha_{\tau_i,\tau_j}$$

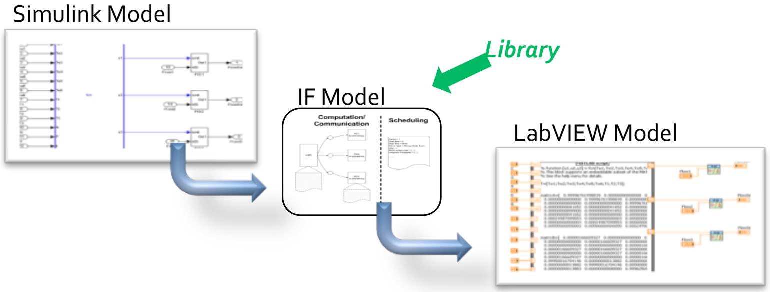
CASE STUDY OF
THE SOFTWARE SYNTHESIS FLOW

Case Study - Hierarchical Room Temperature Control

Function model (two-level controller)



IF Translation



Comparison of Simulink model and LabVIEW model

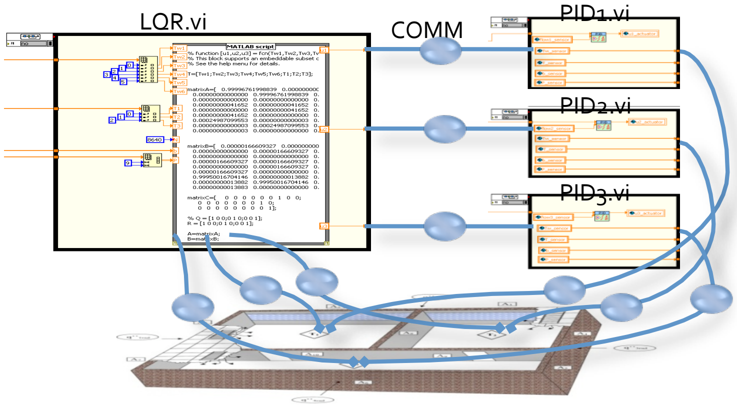
Room Temp	Room1	Room2	Room3
Average Difference	0.304%	0.304%	0.419%
Maximum Difference	4.36%	4.36%	4.63%

Cumulative Air Flow	Room1	Room2	Room3
Difference	1.38%	1.38%	1.53%

- Part of the simulation differences come from PIDs
- Used a lower abstraction level for more precision, and reduced the difference by 10 times compared to the higher level translated model.

Mapping & Communication Interface

- Use communication protocols proposed in *[Benveniste et.al, "Loosely Time-Triggered Architectures based on Commnication-by-Sampling", 2007]*
- Simulate the distributed model in LabVIEW
  - PEs with local clocks (different periods and offsets are set)
  - Communication modeling: 1. abstract latency annotation, 2. specific protocol (currently use TCP/IP).



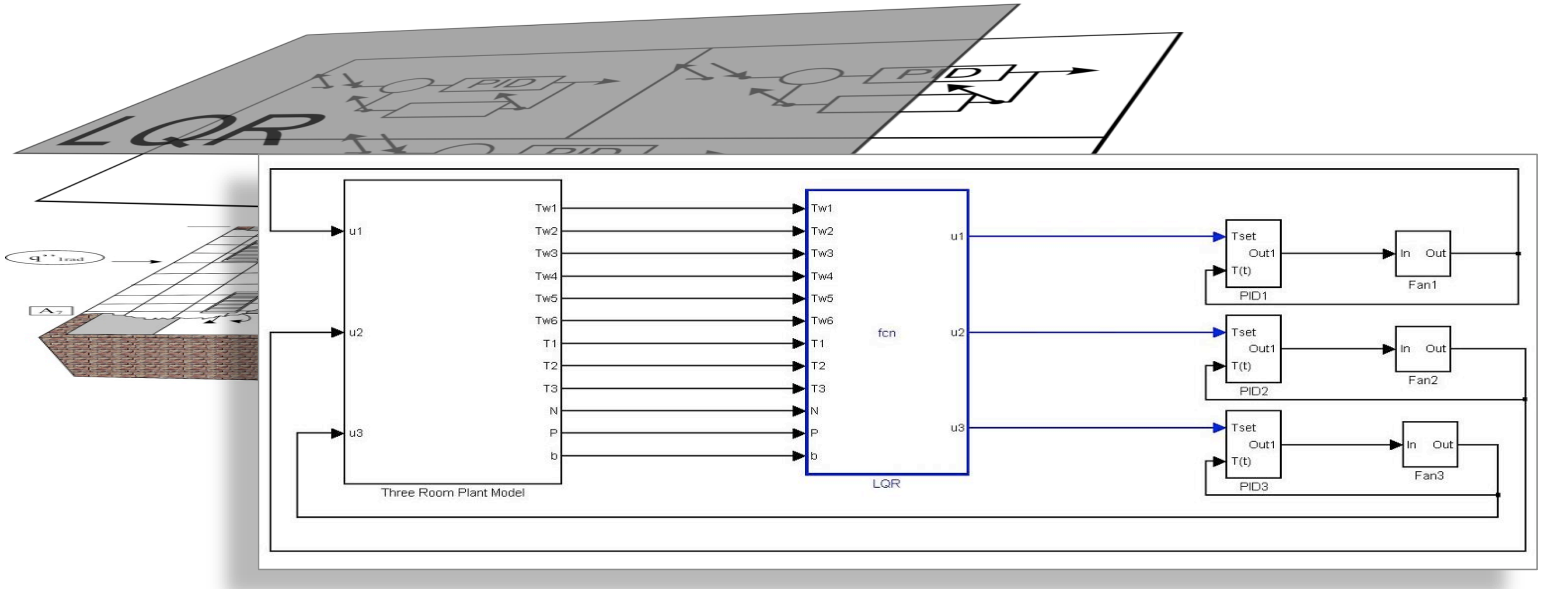
Comparison of centralized model and distributed model

Room Temp	Room1	Room2	Room3
Average Difference	$9.81*10^{-3}$%	$8.72*10^{-3}$%	0.0103%
Maximum Difference	0.801%	0.771%	0.726%

Cumulative Air Flow	Room1	Room2	Room3
Difference of Total Mass Flow	0.0601%	0.0556%	$9.52*10^{-3}$ %

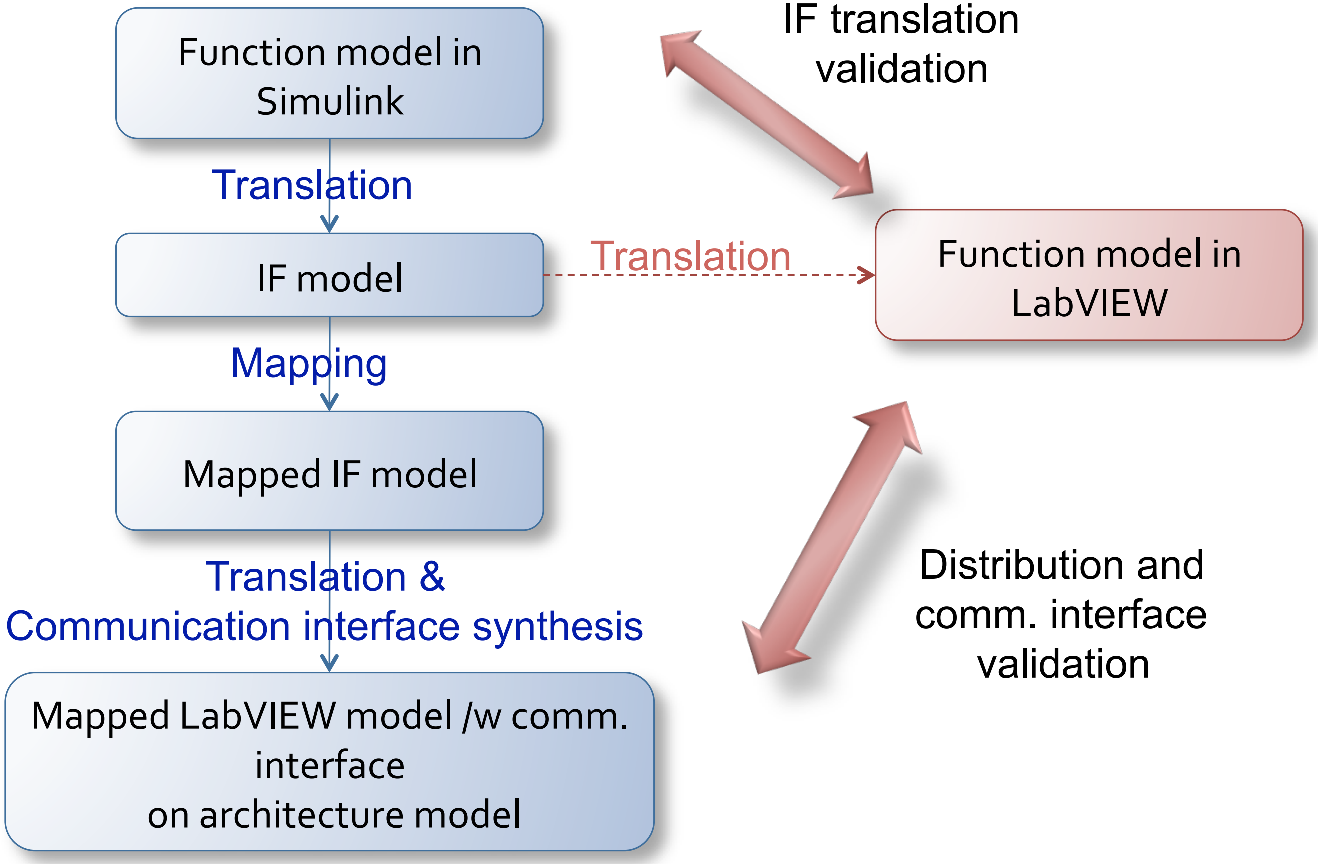
Hierarchical Room Temperature Control

- Function model (two-level controller)



Simulink Model

Case Study Flow



Function model in Simulink

Translation

IF model

Translation

Function model in LabVIEW

IF translation validation

Mapping

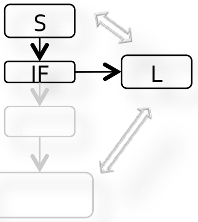
Mapped IF model

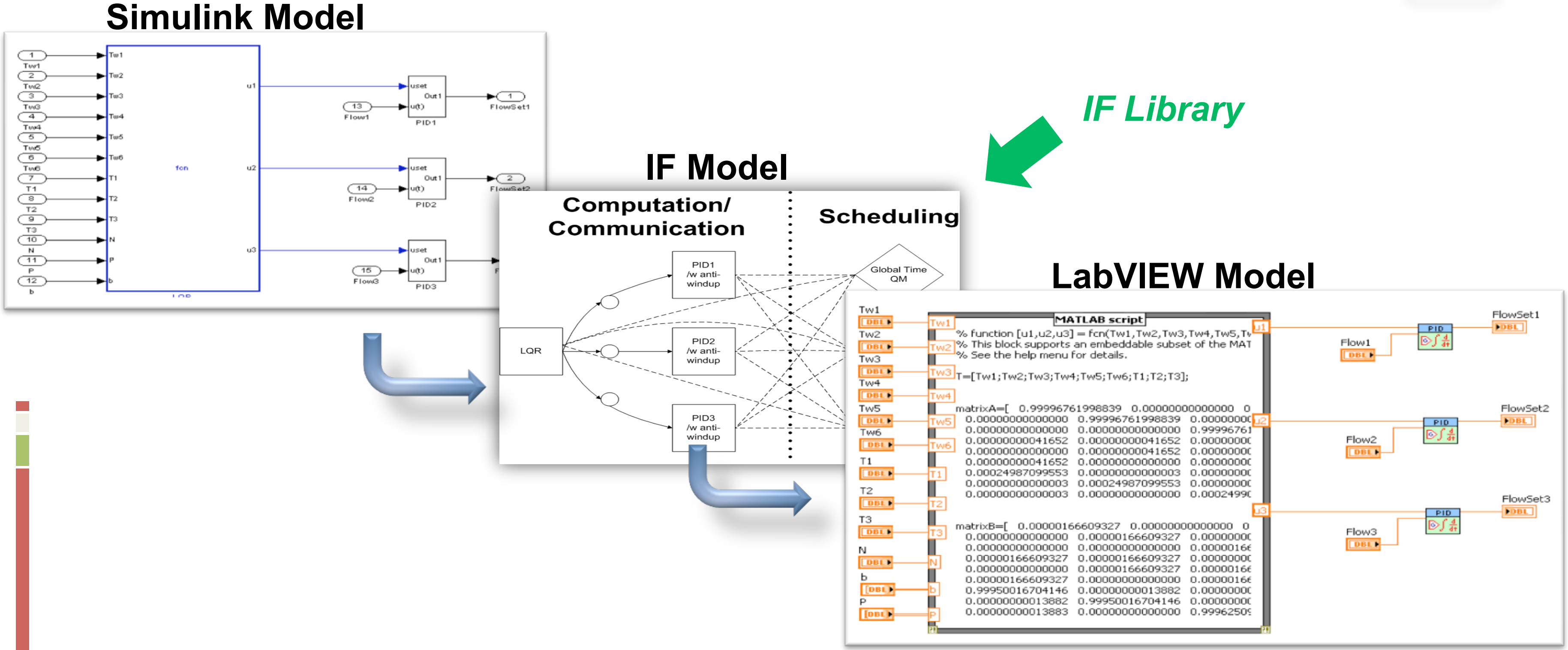
Translation & Communication interface synthesis

Mapped LabVIEW model /w comm. interface on architecture model

Distribution and comm. interface validation

IF Translation





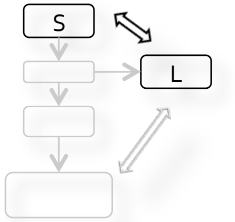
Simulink Model

IF Model

IF Library

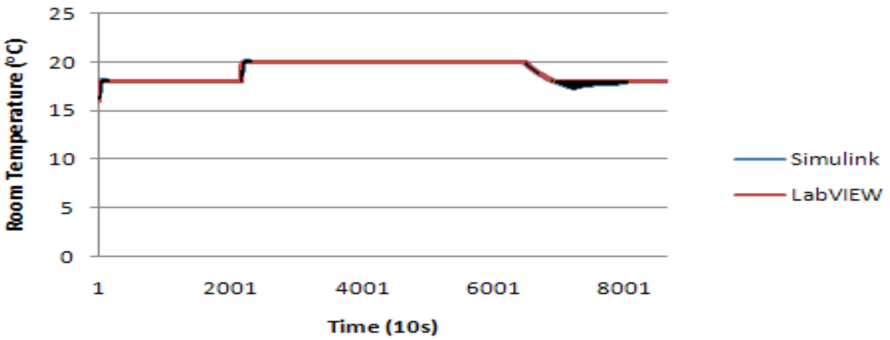
LabVIEW Model

```
% function [u1,u2,u3] = fcn(Tw1,Tw2,Tw3,Tw4,Tw5,Tv
% This block supports an embeddable subset of the MAT
% See the help menu for details.

T=[Tw1;Tw2;Tw3;Tw4;Tw5;Tw6;T1;T2;T3];


matrixA=[  0.99996761998839  0.00000000000000  0
   0.00000000000000  0.99996761998839  0.0000000C
   0.00000000000000  0.00000000000000  0.9999676I
   0.00000000041652  0.00000000041652  0.0000000C
   0.00000000000000  0.00000000041652  0.0000000C
   0.00000000041652  0.00000000000000  0.0000000C
   0.00024987099553  0.00000000000003  0.0000000C
   0.00000000000003  0.00024987099553  0.0000000C
   0.00000000000003  0.00000000000000  0.0002499C


matrixB=[  0.00000166609327  0.00000000000000  0
   0.00000000000000  0.00000166609327  0.0000000C
   0.00000000000000  0.00000000000000  0.0000016€
   0.00000166609327  0.00000166609327  0.0000000C
   0.00000000000000  0.00000166609327  0.0000016€
   0.00000166609327  0.00000000000000  0.0000016€
   0.99950016704146  0.00000000013882  0.0000000C
   0.00000000013882  0.99950016704146  0.0000000C
   0.00000000013883  0.00000000000000  0.9996250
```

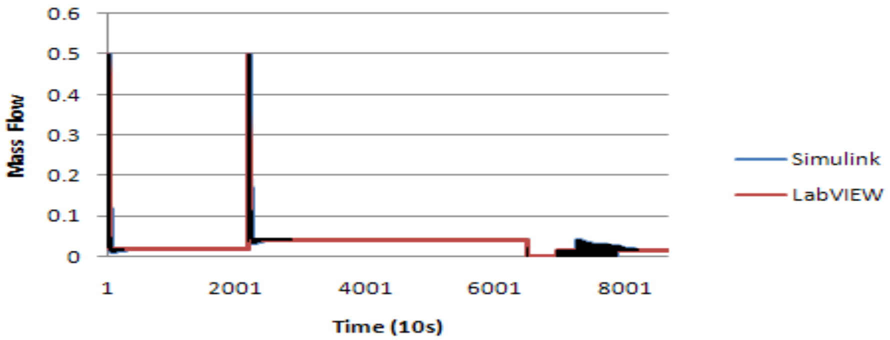


Comparison of Simulink and LabVIEW Functional Models

Comparison of Temperature - Room1



Comparison of Air Flow - Room1

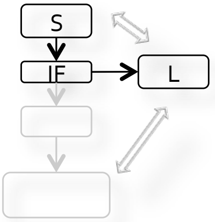


Comparison of Room Temperatures

	Room1	Room2	Room3
Average Difference (°C)	0.0538	0.0538	0.0744
Maximum Difference (°C)	0.741	0.741	0.797

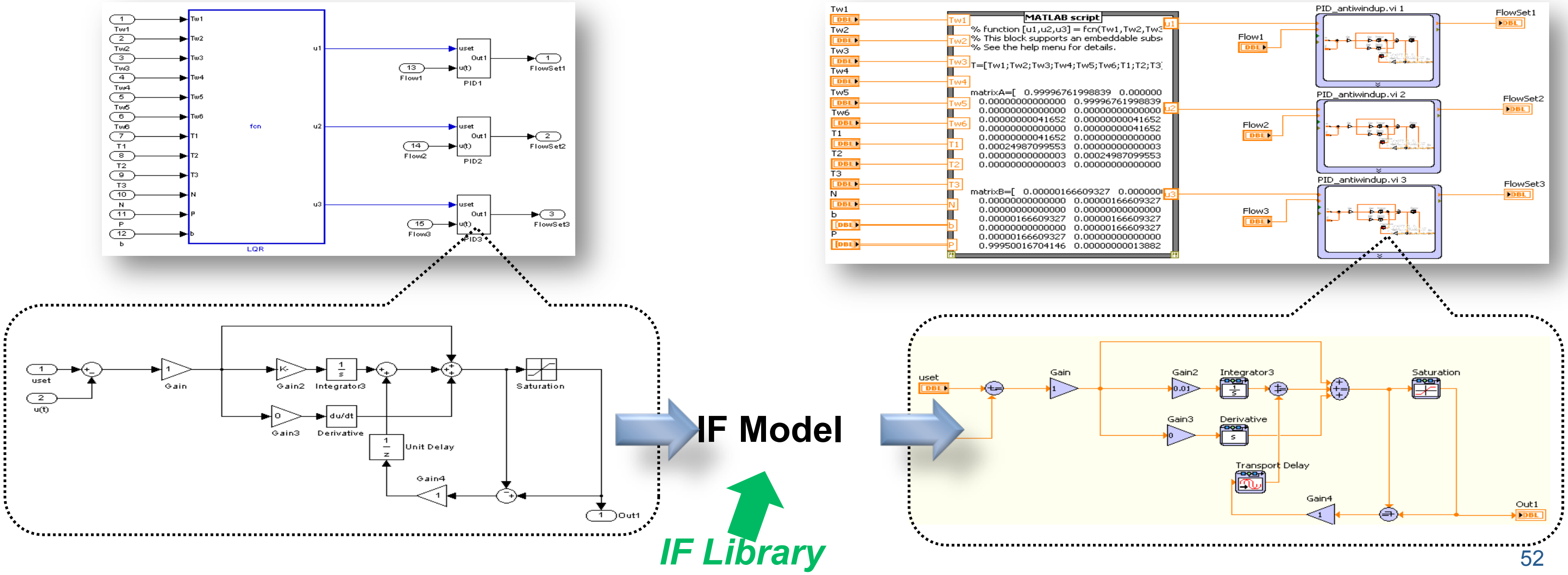
Comparison of Cumulative Air Flow

	Room1	Room2	Room3
Difference of Total Air Flow	1.29%	1.29%	1.55%



IF Translation at Lower Level

- Simulation differences might come from PIDs
- Use a lower abstraction level for more precision.



Simulink Model

LabVIEW Model

```
% function [u1,u2,u3] = fcn(Tw1,Tw2,Tw3
% This block supports an embeddable subs
% See the help menu for details.

T=[Tw1;Tw2;Tw3;Tw4;Tw5;Tw6;T1;T2;T3]


matrixA=[  0.99996761998839  0.000000
  0.00000000000000  0.99996761998839
  0.00000000000000  0.00000000000000
  0.00000000041652  0.00000000041652
  0.00000000000000  0.00000000041652
  0.00000000041652  0.00000000000000
  0.00024987099553  0.00000000000003
  0.00000000000003  0.00024987099553
  0.00000000000003  0.00000000000000


matrixB=[  0.00000166609327  0.000000
  0.00000000000000  0.00000166609327
  0.00000000000000  0.00000000000000
  0.00000166609327  0.00000166609327
  0.00000000000000  0.00000166609327
  0.00000166609327  0.00000000000000
  0.99950016704146  0.00000000013882
```

IF Model

IF Library

Accuracy at Different Abstraction Levels

Accuracy of Room Temperatures

	Room1	Room2	Room3
Average Difference (°C)	0.0538	0.0538	0.0744
Maximum Difference (°C)	0.741	0.741	0.797

Accuracy of Cumulative Air Flow

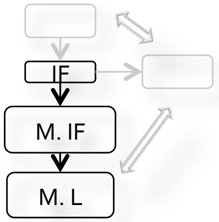
	Room1	Room2	Room3
Difference of Total Air Flow	1.29%	1.29%	1.55%

Lower abstraction level

10^2 ~ 10^3 times less in Average

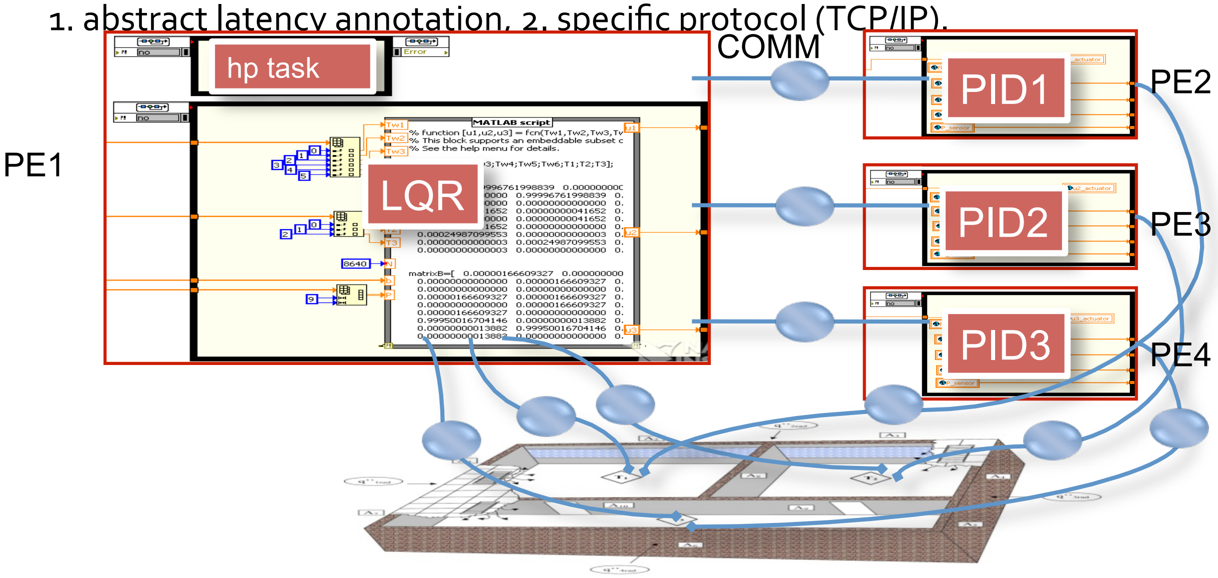
	Room1	Room2	Room3
Average Difference (°C)	2.02×10^{-3}	2.02×10^{-3}	4.15×10^{-3}
Maximum Difference (°C)	0.0555	0.0555	0.0880

	Room1	Room2	Room3
Difference of Total Air Flow	6.26×10^{-3} %	6.26×10^{-3} %	8.15×10^{-4} %

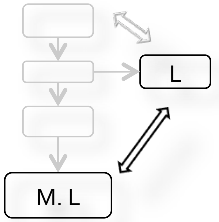


Model Distribution and Communication

- Manual mapping, explore automatic algorithms in the future.
- Communication interface implemented.
- Simulation model in LabVIEW
  - PEs with local clocks (different periods and offsets are set in LabVIEW)
  - Communication modeling:
    1. abstract latency annotation, 2. specific protocol (TCP/IP).



Comparison of Functional Model and Distributed Implementation



- With abstract latency annotations and period settings that guarantee 1-bounded queues:

  Difference = 0

- With TCP/IP:

Comparison of Room Temperatures

	Room1	Room2	Room3
Average Difference (ºC)	0.0181	0.0173	0.0233
Maximum Difference (ºC)	0.429	0.421	0.211

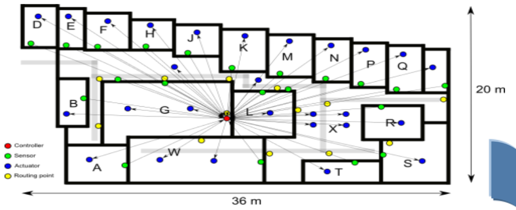
Comparison of Cumulative Air Flow

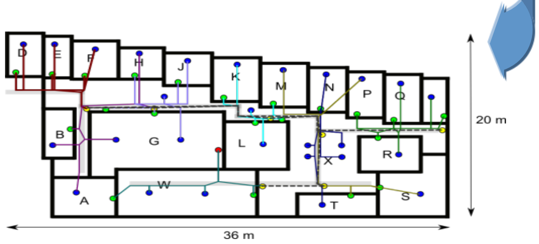
	Room1	Room2	Room3
Difference of Total Mass Flow	0.565%	0.518%	0.926%

Communication Synthesis

Building upon the COSI framework

COSI Synthesis (DOP Center example)



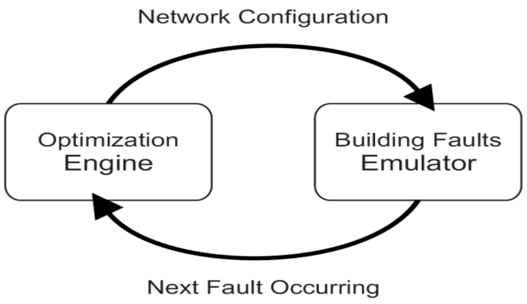


Sensor to controller
-Latency: 0.3 s
-Message length: 8 bits
-Period :1 s

Controller to actuators
-Latency: 0.4 s
-Message length:16 bits
-Period:1 s

Network library
-Field bus 78kb/s (ARCNET)
-Field bus 2.5Mb/s (ARCNET)
-Constraints: topology, degree, length
-Two level hierarchical network

8 Networks (2.5Mb/s) plus a
high speed, second level network
-Estimated cost $21385
-Bus load: 96kb/s(min), 237kb/s(max),
139kb/s(avg), Networks are distance
and degree limited, not bandwidth limited

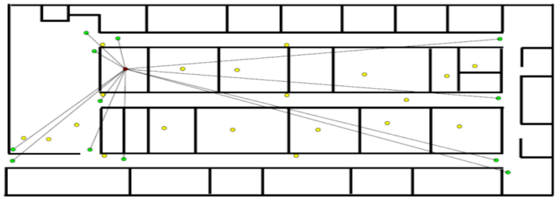


Network Configuration

Optimization Engine

Building Faults Emulator

Next Fault Occurring



- Zigbee network
- Exponentially distributed link failures
- Node failure based on battery life
- Optimal re-routing

Further development

- Added wireless models (Zigbee)
- Design flow and optimization for node placement and optimal routing
- Added scheduling of flows in beacon-enabled Zigbee networks
- Dynamic reconfiguration (started)

Required effort

Development of NOS, diagnostics, reconfiguration