A Computer Science View of THE LOAD

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Where does the energy go?
… Buildings

- People
- Supply Air
- Water
- Electricity
- Return Air
- Waste Water
- Heat

Sun
Supply

Demand

Figure Courtesy Professor Arun Majumdar, UCB, LBNL

Merger

Electricity Generation, Transmission & Distribution Losses

Distributed Electricity

Useful Energy

Lost Energy
BUILDINGS CONSUME SIGNIFICANT ENERGY

The Numbers Tell the Story

$370 Billion
Total U.S. Annual Energy Costs

200%
Increase in U.S. Electricity Consumption Since 1990

40%
Total U.S. Energy Consumption for Buildings

72%
Total U.S. Electricity Consumption for Buildings

55%
Total U.S. Natural Gas Consumption for Buildings

Buildings construction/renovation contributed **9.5%** to **US GDP** and employs approximately **8 million people**. Buildings’ utility bills totaled **$370 Billion** in 2005. Buildings use **72%** of the electricity and **55%** of the nation’s natural gas.

Source: Buildings Energy Data Book 2007
EPA Nat Action Plan for Energy Efficiency

- 30% of energy consumed in buildings is wasted
- 66% electrical, 34% gas and other
- 15.5 kWh per square foot

* 2003 EIA Commercial Building Consumption Survey
Where does the energy go in buildings?

- HVAC – Heating, Ventilation, Air Conditioning
- Lighting
- Major Equipment
- Plug Loads
Global cost curve of GHG abatement opportunities beyond business as usual

- ~27 Gton CO₂e below 40 EUR/ton (~46% vs. BAU)
- ~7 Gton of negative and zero cost opportunities
- Fragmentation of opportunities
HVAC

• Heating – maintain indoor temperature within comfort threshold
  – ASHRAE 55-1992: 68-75° winter, 73-79° summer (why?)

• Ventilation
  – replacing air in a space to control temperature or remove CO2, contaminants, moisture, odors, smoke, heat, dust and airborne bacteria
  – ASHRAE 62-1999: 20 CFM per person in work environment

• Air Conditioning
  – provides cooling, ventilation, and humidity control

• Provides comfort to people
  – Humidity, Pressure, Acoustics, Visually pleasing, ...
  – Productivity, durability, health, ..
Thermodynamics …

• 0th Law: If two thermodynamic systems are each in thermal equilibrium with a third, then they are in thermal equilibrium with each other.

• 1st Law: Energy can neither be created nor destroyed. It can only change forms.
  – In any process in an isolated system, the total energy remains the same.

• 2nd Law: The total entropy of any isolated thermodynamic system always increases over time, approaching a maximum value.

• 3rd Law: the entropy of all systems and of all states of a system is zero at absolute zero"
Heat Transfer

• **Conduction**
  – Energy transferred when free atoms collide
  – 2\textsuperscript{nd} law: from higher to lower
  – Via a medium (solids, liquids, gas)

• **Convection**
  – Displacement of molecule groups at a different temperature
  – Transfer of enthalpy

• **Radiation**
  – Heat transfer caused by emission and absorption of electromagnetic waves

• **Latent heat**

• **Thermal Resistance (R-Value)**
  • $U = 1/R$
  • Heat Flux: $Q = U \times A \times \Delta T$

U-Value is the rate of heat flow in Btu/h through a one ft\textsuperscript{2} area when one side is 1\textdegree F warmer
Heat Gains

- Solar Heat Gain
- Occupants
- Equipment
- ...

- The amount of solar heat energy allowed to pass through a window

- Example: SHGC = 0.40
  Allows 40% through and turns 60% away
Psychrometrics

• psychrometric ratio
  – ratio of the heat transfer coefficient to the product of mass transfer coefficient and humid heat at a wetted surface

• Specific enthalpy
  – symbolized by $h$, also called heat content per unit mass, is the sum of the internal (heat) energy of the moist air in question, including the heat of the air and water vapor within
HVAC Equipment

- Fans / Blowers
- Furnace / Heating Unit
- Filters
- Compressor
- Condensing Units
- Evaporator (cooling coil)
- Control System
- Air Distribution System
  - Ducts, dampers, ...
Building HVAC: Ventilation

- Supply Air Fan
- Exhaust Air Fan
- Return Air Vent
- Air Vent
- Zone
Building HVAC: AHU

Supply Air Fan

Air Handling Unit

Exhaust Air Fan

Return Air Vent

Zone

Air Vent
Air Handling Unit (AHU)
Building HVAC: Chilled Water

Supply Air Fan

Exhaust Air Fan

Chilled Water Pump

Air Handling Unit

Zone

Return Air Vent

Air Vent
Building HVAC: Chiller

- Supply Air Fan
- Exhaust Air Fan
- Chilled Water Pump
- Air Handling Unit
- Chiller
  - Condenser
  - Refrigerant
  - Expansion Valve
  - Evaporator
- Compressor
- Return Air Vent
- Zone
- Return Air Vent
- Refrigerant

Diagram shows a part of the HVAC system with various components and their connections.
Major Equipment

- Chillers
- Boilers
- Cooling Towers
Building HVAC: Zone Control

- Cooling Tower
- Condenser Pump
- Chiller
  - Expansion Valve
  - Refrigerant
  - Condenser
  - Evaporator
- Chilled Water Pump
- Air Handling Unit
- Supply Air Fan
- Exhaust Air Fan
- Return Air Vent
- Zone
- Reheater
- Damper
- Air Vent
Heating

• AHU Cool + Zone Reheating
• AHU + Boiler
• Distribute Hot and Cool H2O and mix at zone
• Circulate hot H2O + Radiator separate from VAC
System Types and Terms

- Packaged Rooftop Unit
- Split System
- Heat Pump
- Geothermal
- Air to Air
- Hydronic (water)
- (Packaged Thermal) PTAC / PTHP
- Constant Volume
- Variable Volume
- Indoor Air Quality
- Direct Expansion
Heat Pump
Soda HVAC components

- Chillers: 2 x 130 kw
- Colling Towers: 2 x 33.2 kw
- Computer Room units: 12 x 45 kVA
- AHU SF: 3.2 kw
- AHU RF: 2.3 kw
- Economizers: 4 x 2.6 kw + 2.1 + 1.4
- Supply fans: 4 x 2.3 kw + 1.4
- Pumps: 2 x 9.3 kw + 2 x 14 kw
- Compressors: 2 x 5 kw

- It’s all duty cycle
Soda Chilled Water

- Blow cold air throughout building
- Maintain circulation
- Adjust cooling with vents and VFDs
- Heat it where needed
- AC determined by needs of the worst heat load
  - Comm closet
Soda Electrical

2x Substation

12 KV dist.

Machine Rooms
Offices
Classrooms

2x Chiller

~42 circuits each

1200 A 277/480 3 phase

2500 A 120/208 3 phase

Lighting
Pumps
Fans

MCM1

MCM2

HP1A 400

HP1A 400

HP2A 600

HP3A 400

HP4A 400

HP5A 400

HP6A 100

HP7A 400

LP1A 400

LP1B 400

LP2A 800

LP2B 225

LP2C 225

LP2D 225

LP2E 225

LP2F 225

LP2G 225

LP2H 225

LP2I 225

LP2J 225

LP2K 225
HVAC Control

- Building is designed for max cool/heat load
- Operates at partial load
- Varies with weather, activity, building configuration
- HVAC control affects this “partial load service”
- Within operational constraints
  - Zonal temps
  - Adequate airflow
  - Air pressure
  - Flow and pressure throughout the system
  - Energy efficiency
  - Maintenance efficiency
Controlled Parameters and Points

• Temperature
• Humidity
• Ventilation
• Pressure
• Flow Rate
• …

• Mechanical Room – Primary equipment
  – Chiller, boiler, pumps, heat exchanged

• Secondary equipment – AHU “weather maker”

• Room controls
  – Zone thermostats, humidistats, …
  – Fan coil units, variable air volume units, terminal reheat, unit vents, exhausters
Why Controls

• 1) Maintain thermal comfort conditions
• 2) Maintain optimum indoor air quality
• 3) Reduce energy use
• 4) Safe plant operation
• 5) To reduce manpower costs
• 6) Identify maintenance problems
• 7) Efficient plant operation to match the load
• 8) Monitoring system performance
Open Loop (feed forward) Control

• a type of controller which computes its input into a system using only the current state and its model of the system
  – No feedback

• Typically exerts control points according to a schedule

• Works well when there is an accurate model of how the plant responds
Closed Loop (Feedback) Control

- **Types of Feedback Control**
  - Two-position, on/off, bang-bang
  - Modulated, continuous

- **Means of Control**
  - Direct acting – e.g., radiator release value
  - Electric / Electronic – e.g., bi-metallic strip with relay
  - Pneumatic
  - Direct Digital Control
  - Mixed
Simple Closed-Loop Control

- Set point
- Tolerance / Band
- Sensing
- Action
- Calibration
- Model and Assumptions
Two Position Control example

Load controller
Furnace

24 v AC @ ~10 mA

Electrical connections
Adjustment
Contacts
Low expansion metal
High expansion metal
Magnet

Bi-Metallic Thermostat

Capillary tube
Bulb
Diaphragm
Post
Spring
Movement

Bulb & Capillary Sensor

Capillary to remote sensing bulb
Bellows
Contacts
Adjustment

Sealed Bellows Temperature Sensor
Sensors

• Temperature
  – Resistance Temperature Device (RTD)
  – Thermistor
  – Thermocouple

• Relative Humidity
  – Resistance humidity sensors
  – Capacitance humidity sensors
  – Quartz crystal humidity
  – Temperature compensation, condensation

• Pressure
  – Variable resistance
  – Capacitance

• Flow Sensors
  – Orifice
  – Venturi
  – Flow nozzels
  – Vortex shedding
  – Positive displacement
  – Turbine based
  – Magnetic
  – Ultrasonic

• Air flow
  – Hot wire anemometer
  – Pitot – static tube

• Dew point
  – Hygrometers

• Liquid level
  – Hydrostatic, ultrasonic, capacitance

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An Analog World

- **Transducers**
  - Allow us to convert physical phenomena to a voltage potential in a well-defined way.

\[ \text{Volts} = 0.00355 \times \text{TEMP} + 0.986 \]
Simplest Analog Device

- Often think of it as an actuator, rather than a sensor
  - But that’s because of the circuit we put it in
- It is binary (two states) but why is it not digital?
To Sample a switch, make it digital

- Many sensor are switches
- Two “states” but not digital
  - Open => no current
  - Closed => no voltage drop
- Cap charges to V_{acc} when open
- Cap discharges to GND when closed
Analog to Digital

• What we want

Physical Phenomena → Sensor → ADC → Software → ADC Counts → Engineering Units

• How we have to get there
Modulated Sensor Example

• What will you measure across an RTD?
• Many sensors modulate current
  – 4-20 mA standard
  – Why 4 mA => 0 ?
Ratiometric sensor

- $V_a = V_{acc} \times R_{sens} / (R_{comp} + R_{sens})$
- use $V_{ref} = V_{acc}$
- $D = M \times R_{sens} / (R_{comp} + R_{sens})$
Example Modulated Control
Controller Issues

• Partial-load via on/off control means everything is starting and stopping
  – Costly in energy, efficiency, maintenance

• Modulation by wasting is not attractive either

• New technology options
  – Variable air vent
  – Variable frequency drives

1 hp = 746 watts
## Matching Sensor & Control

<table>
<thead>
<tr>
<th>Controller Action</th>
<th>Heating, Humidification, Pressure (sensed downstream from controlled device)</th>
<th>Cooling, Dehumidification, Pressure (sensed upstream from controlled device)</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Fails to ON</td>
<td>Direct Action</td>
<td>Reverse Action</td>
</tr>
<tr>
<td>Normally open ports, valves or dampers</td>
<td></td>
<td></td>
</tr>
<tr>
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![Direct Action Controller](image1)

![Reverse Action Controller](image2)

*Graphs showing mA vs Room Temperature for Direct and Reverse Action Controllers.*
Computational plumbing

- Building needs hotter water for heat on cold days
- OAT secondary sensor changes setpoint for on/off pan heater
The Controlled Processes

- Example – flow rate in heating/cooling coils in heat exchangers
Matching controller & actuator

- Also need to worry about sensor & actuator effect
  - Air flow, pressure, ...
Controller Responses

• 1) Two-position
  – Complete stroke

• 2) Floating
  – Fast airside control loops
  – E.g., Two position dampers

• 3) Proportional
  – \( Y = -kp \ Q \)

• 4) Proportional plus Integral (PI or P+I)
  • \( Y = -ki \ Q dt \)
  • control action is taken proportional to the integral of deviation Q

• 5) Proportional plus Integral plus Derivative (PID or P+I+D)
Direct Digital Control !!!
Building Management Systems

- 1300 sense / ctrl points in Soda Hall
- Vast database of action / effect
- No science to turning all the knobs
Building Management Systems
Economizers
Economizers

- Economizers provide “free cooling” when outdoor conditions are optimal
- Proper orientation & zoning yields comfort & efficiency
Resources

• ASHRAE –The American Society of Heating, Refrigerating and Air-Conditioning Engineers  
  www.ashrae.org

• www.energycodes.gov

• http://www.demandless.org/building/

• http://www.epa.gov/cleanenergy/documents/sector-meeting/4bi_officebuilding.pdf

• http://sustainability.berkeley.edu/

• www.buildingscience.com

• http://www.southface.org
Questions

• How much load can be sculpted?
• How much of the peak can be shaved? Versus baseline?
• What is the opportunity for sophisticated model-driven control?
• Where to sense what?
• What are the physical resources to abstract? Higher level abstractions?
• What would “building applications” be?
• How can it interact proactively with the grid?
• How much can be done with improvements versus new design of the envelope?