Real-Time Optimization of a Building CHP/Thermally Driven Space Conditioning System using Model Predictive Control

IBPSA 2011 Model Predictive Control in Buildings Workshop

Montreal

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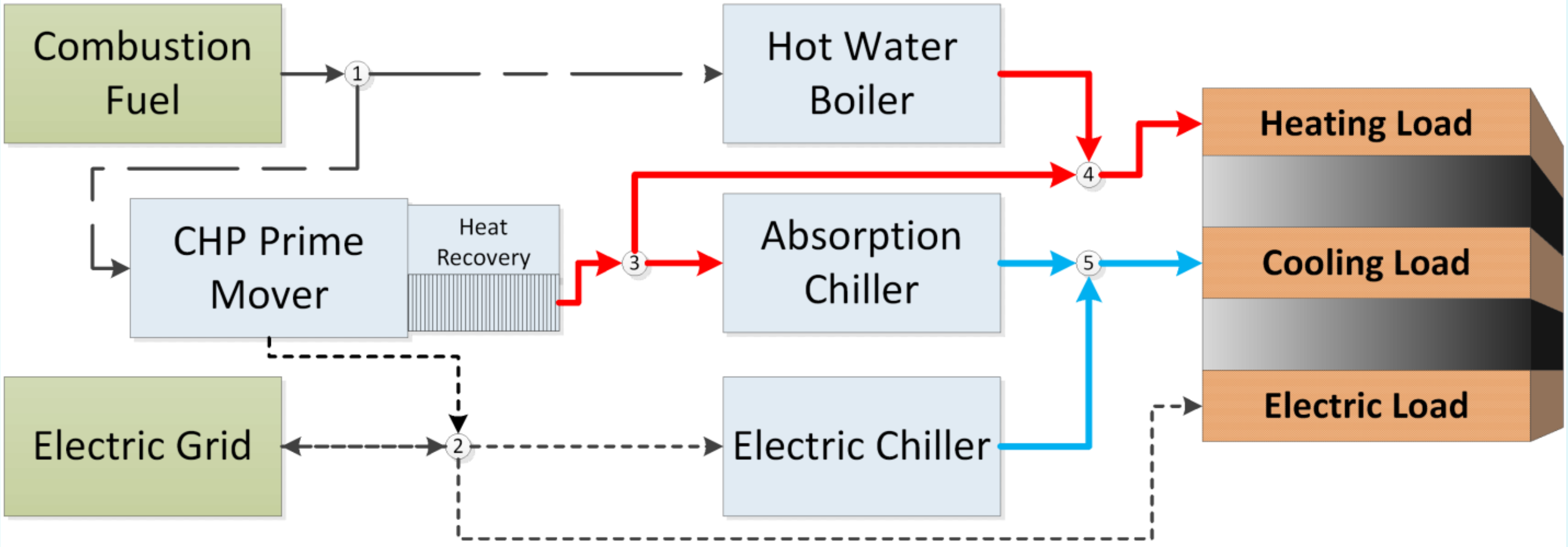
Motivation

- Building systems are becoming more complex combinations of sub-systems, equipment and components
- Each sub-system or component has its own performance characteristics that depend on loading and conditions
- Overall performance and energy efficiency are difficult or impossible to predict based on intuition alone
- Control strategies for obtaining optimum (or near optimal) performance requires some method for accounting for interactions between components, and with the environment and building occupants
- For real-time predictive control, processing must be “fast” relative to control cycles

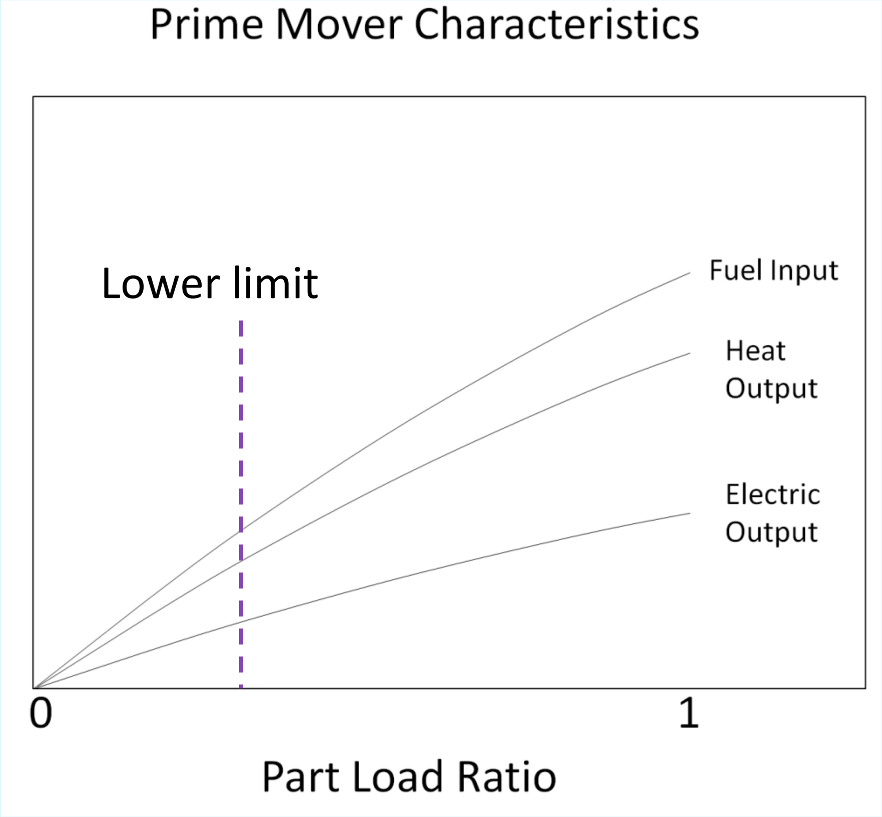
CHP/Thermally Driven System Example

- Illustrates many of the issues and challenges in model predictive control
- Represents a more ambitious class of designs for meeting building service needs
  - Electrical power
  - Space conditioning
- Provides a means for responding to varying dynamic performance goals
  - Energy use or cost
  - Demand response
  - Emissions



Node 1. Fuel distribution point for CHP Prime Mover and Hot Water Boiler
Node 2. Electricity distribution point for Electric Chiller and Building Electric Load. Also includes Electric Grid buyback
Node 3. Thermal energy distribution point from Heat Recovery on the CHP Prime Mover to Absorption Chiller and Building Heating Load
Node 4. Thermal energy distribution point for Hot Water Boiler and CHP Prime Mover feeding Building Heating Load
Node 5. Thermal energy distribution point for Absorption Chiller and Electric Chiller feeding Building Cooling Load

Typical Prime Mover Performance



Need this data for modeling/ simulation

Basic Energy Flows

- The prime mover consumes fuel, generates electrical power and waste heat, a substantial fraction of which is recovered by the heat recovery unit
- The site generated electrical power is used to meet the building electrical load, and any excess is available for the electric chiller or to send to the grid; if there is a deficit, electrical power is drawn from the grid
- The recovered waste heat is available for meeting building heating loads or for the absorption chiller to meet cooling loads
- If heating loads are not met, the auxiliary boiler will provide the needed heating
- The electric chiller can use grid power to meet some or all of the cooling loads

Overview of Methodology

- Performance models are compiled for each component based on load fraction and operating conditions (from manufacturer's testing or operating data)
- Sensors monitor all relevant air and fluid temperatures, fluid flow rates, heat and energy transfers
- Status of current space conditions and equipment loads are verified to confirm that the system is under control and models are accurate
- Cooling and heating coil loads are determined from

$$\dot{q} = \dot{m} c_p \Delta T$$

- Non cooling electrical power is measured at the appropriate locations
- Utility generating efficiency, costs and emissions factors are obtained via Smartgrid or internet

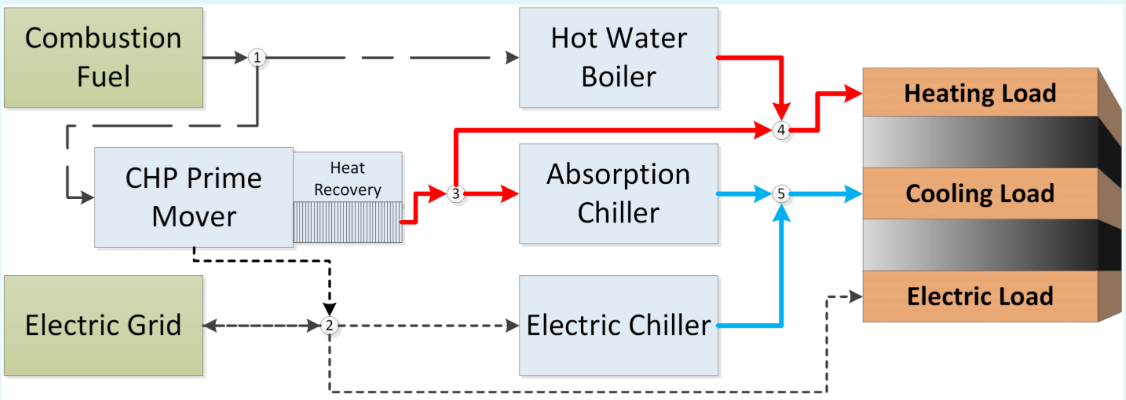
Methodology (2)

- Optimization criteria (objective function) is specified
  - Minimize energy use, cost, emissions or some combination
- Operating constraints are specified
  - Minimum or maximum load ratios or temperatures
  - Limits on rate of change of setpoints
- System is simulated for a quasi-equilibrium condition to determine proposed optimum setpoints
  - Prime mover part load
  - Allocation of recovered heat to absorption chiller and heating load
  - Allocation of cooling load to electric and absorption chillers
  - Allocation of electrical power onsite or to grid

Methodology (3)

- Proposed new setpoints (operating conditions) are checked against constraints and are revised accordingly, if necessary
- Dynamic response of the system and components are monitored to verify expected changes and check for stability
  - Individual component operating conditions are compared to predicted; if substantially different, model or equipment may have a problem
  - Some components (e.g. absorption chiller) may have a slow dynamic response and may require a longer period to evaluate
- Repeat at selected intervals

System Schematic and Capacity



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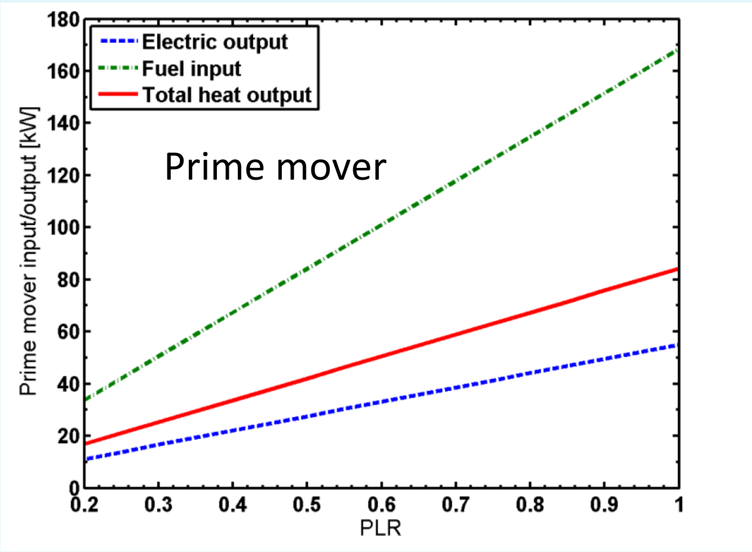
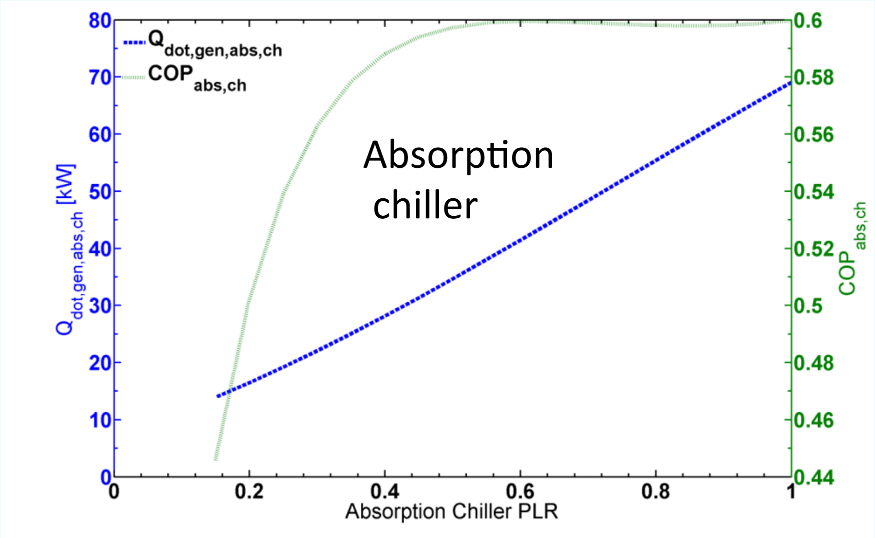
Building Equipment	Capacity
CHP Prime Mover	55 kW Electric, 83.4kW (285 kBtu/h) Thermal
Absorption Chiller	40 kW (136 kBtu/h) Cooling
Electric Chiller	30 kW (102 kBtu/h) Cooling
Hot Water Boiler	100 kW (341 kBtu/h) Heating

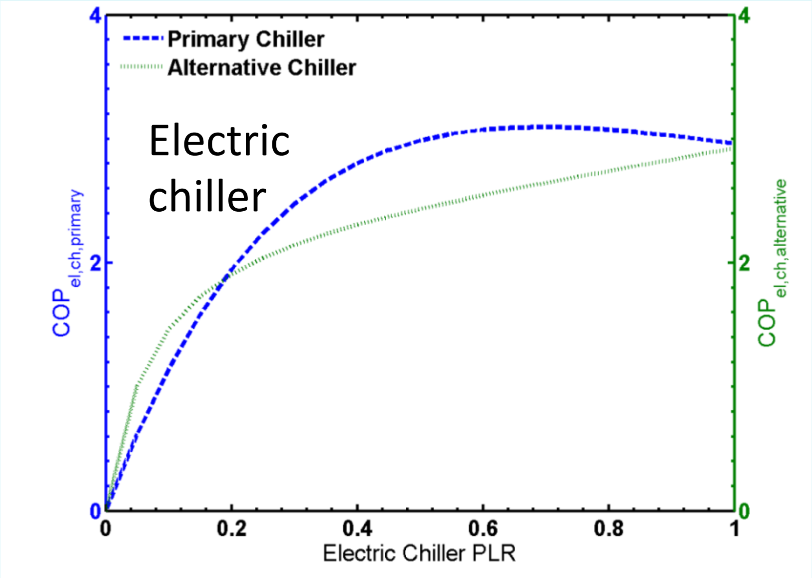
Objective: To assist operators in determining **optimum** component **set points** and operating conditions to **achieve minimum total primary energy rate**.

- Finding this optimum set can be **challenging** due to the **large search space** and multiple degrees of freedom presented by the **four independent components**.

Example Equipment Characteristics

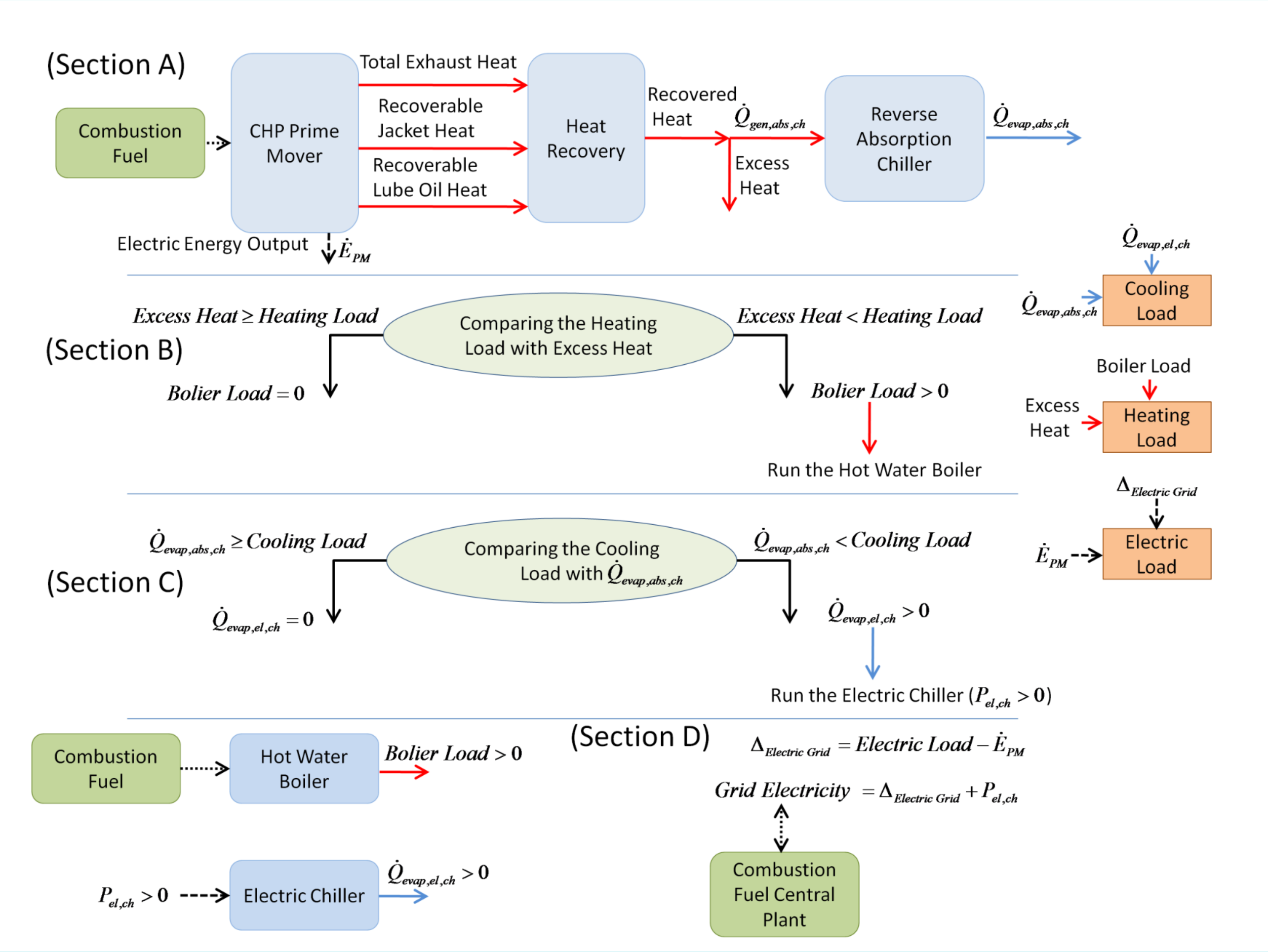






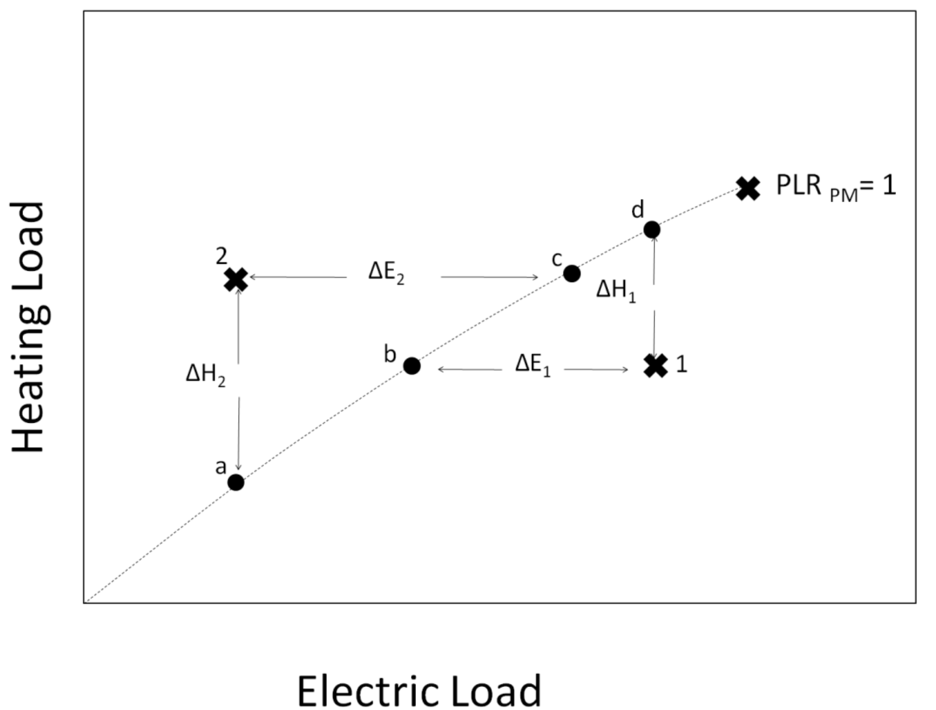
- Pumps
- Fans
- Valves
- Dampers

System Simulation Procedure Implemented in MATLAB



Meeting Electrical and Heating Loads

Prime Mover Electric Power Output and Heating Characteristics



ΔE_1 : Required grid electricity from the grid

ΔH_1 : Excess thermal energy

ΔE_2 : Excess electricity

ΔH_2 : Required heat from the boiler

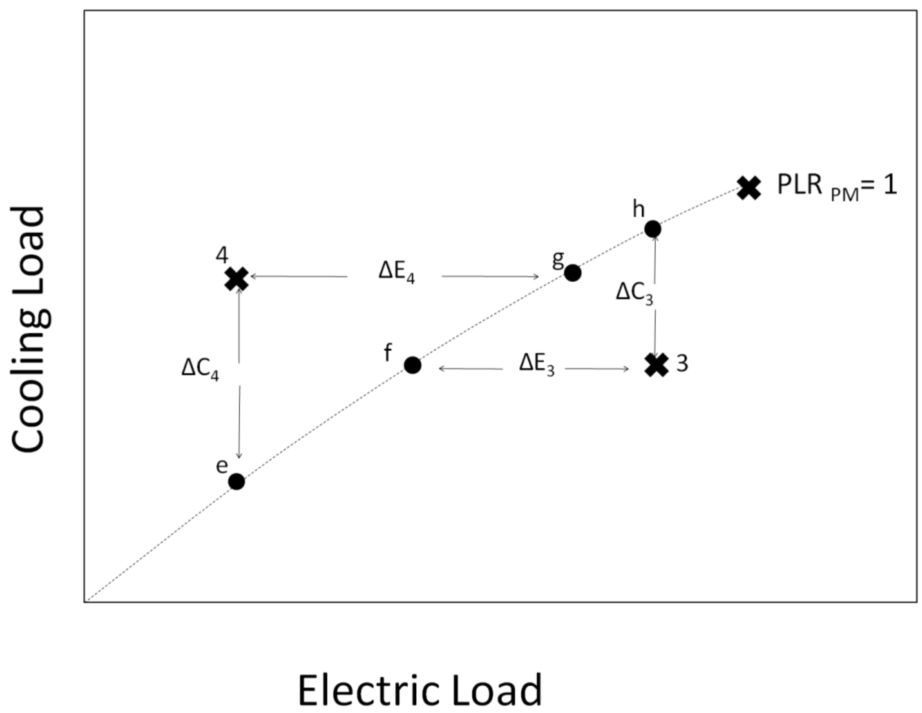
a, d: Electric Load Following (ELF)

b, c: Thermal Load Following (TLF)

- The only electrical/heating load combinations that can be exactly met by the prime mover are those that fall on the curve.

Meeting Electrical and Cooling Loads

Prime Mover Electric Power Output
and Cooling Characteristics (Absorption Chiller)



ΔE_3 : Required electricity from the grid

ΔC_3 : Excess cooling

ΔE_4 : Excess electricity

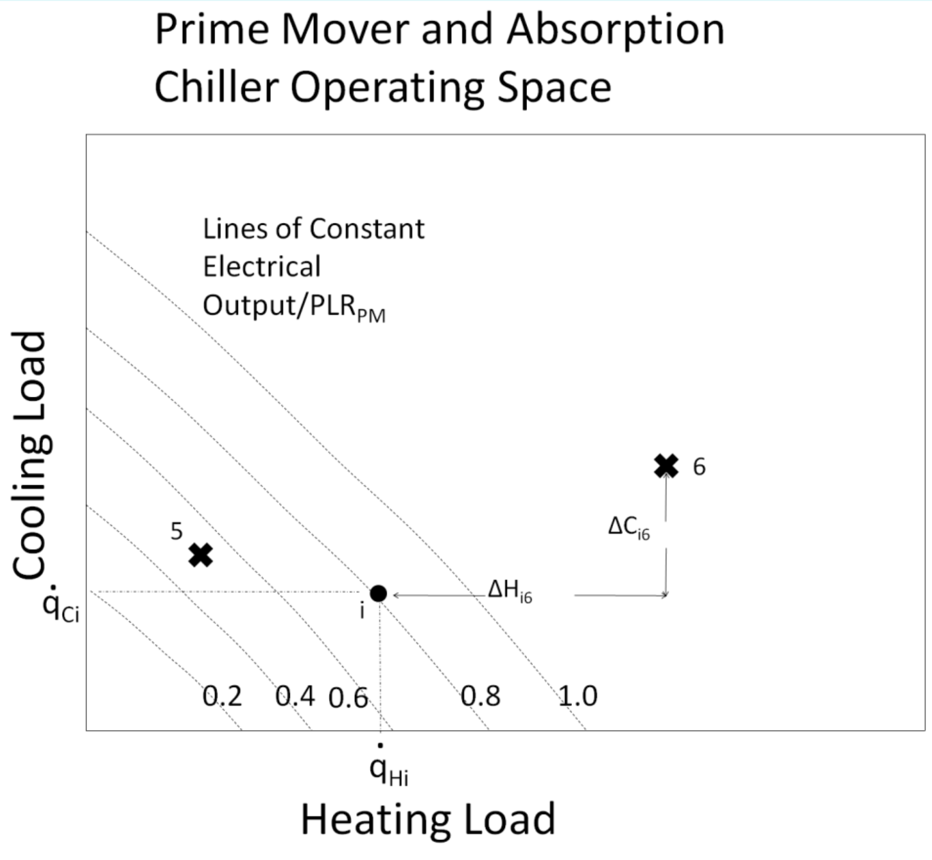
ΔC_4 : Required cooling from the electric chiller

e, h: Electric Load Following (ELF)

f, g: Thermal Load Following (TLF)

(zero heating loads)

Meeting Electrical, Heating, and Cooling Loads



$\dot{q}_{Hi}$: Heating contributed by the prime mover

$\dot{q}_{Ci}$: Cooling contributed by the absorption chiller

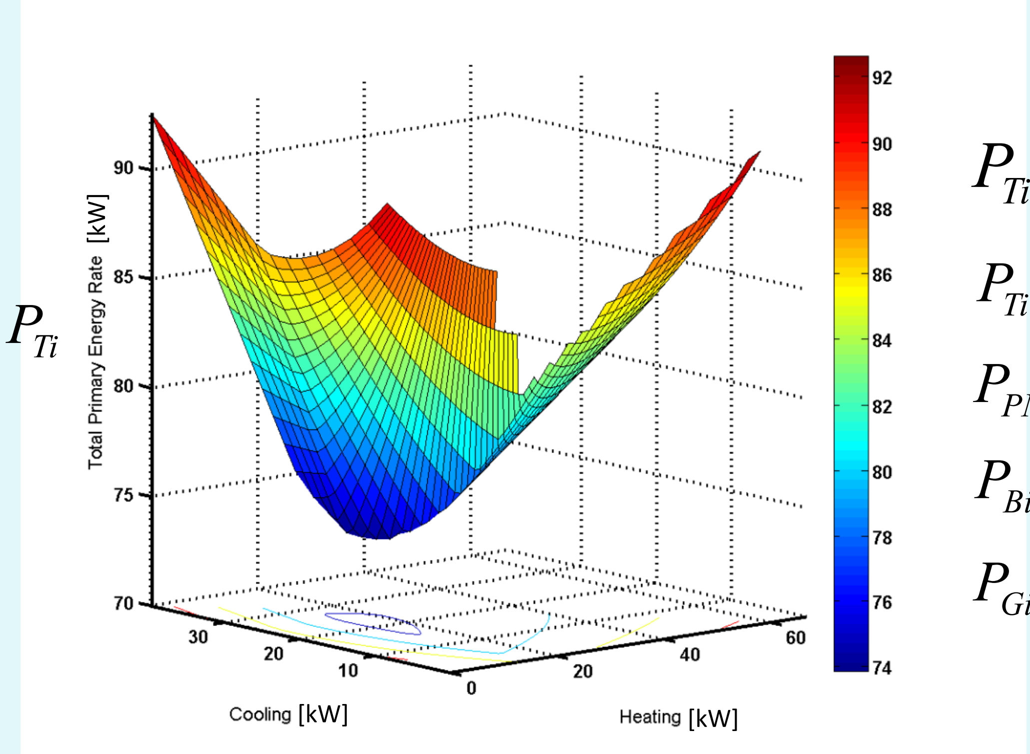
ΔH_{i6} : Heating contributed by the boiler

ΔC_{i6} : Cooling contributed by the electric chiller

- Electrical, heating, and cooling loads

- The labeled curves represent constant electrical power outputs, which correspond to fixed thermal outputs that can be allocated for heating or cooling purposes in any manner.
- What is the **optimum PLR** for the prime mover?
- What is the **optimum thermal output fraction** applied to **heating** and **cooling**?
- We can **compute** the **total primary energy input rate** for **each point** (e.g. point i).

Objective Function



$$P_{Ti} = P_{PMi} + P_{Bi} + P_{Gi}$$

P_{Ti} : Total energy input rate

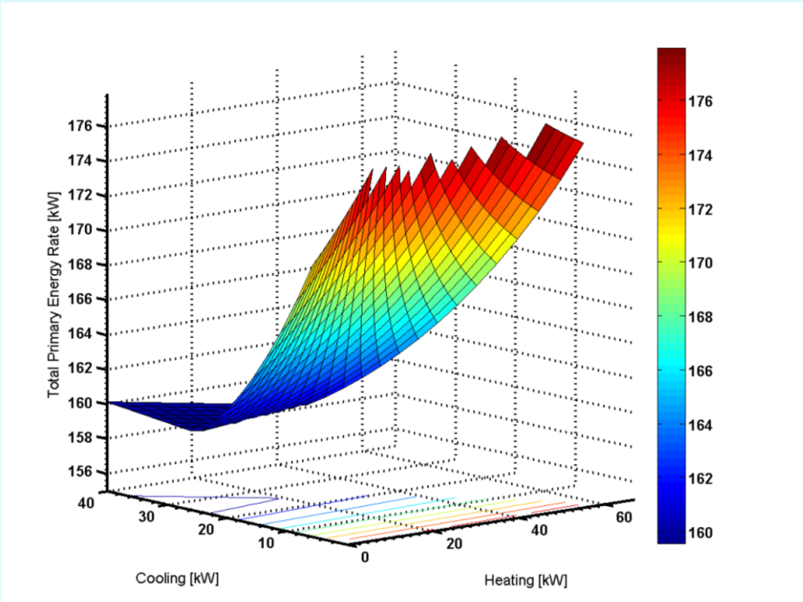
P_{PMi} :Prime mover energy input rate

P_{Bi} : Boiler energy input rate

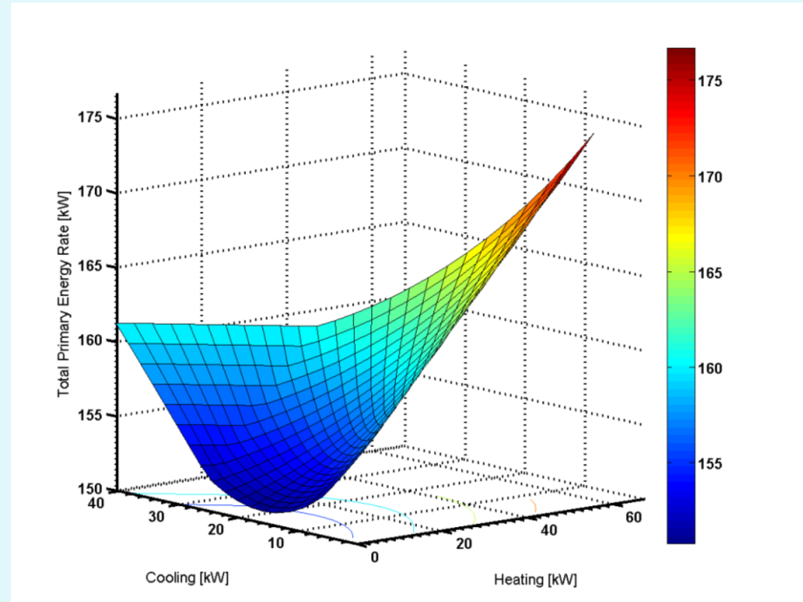
P_{Gi} : Grid energy input rate

- The **method** substantially compresses the search space, reduces the computational burden and **generates** a **performance map** that can be used to visually or analytically determine the best operating condition.

Variation in Electrical Grid Efficiency



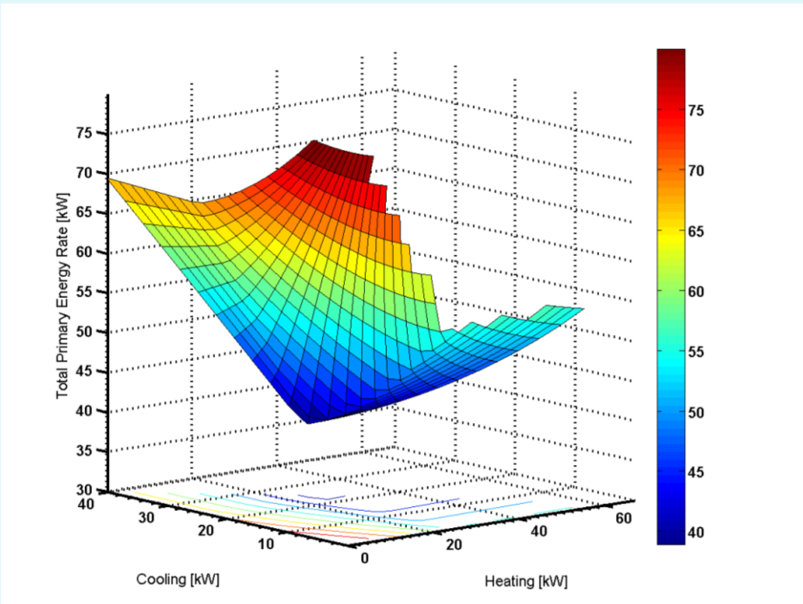
2a



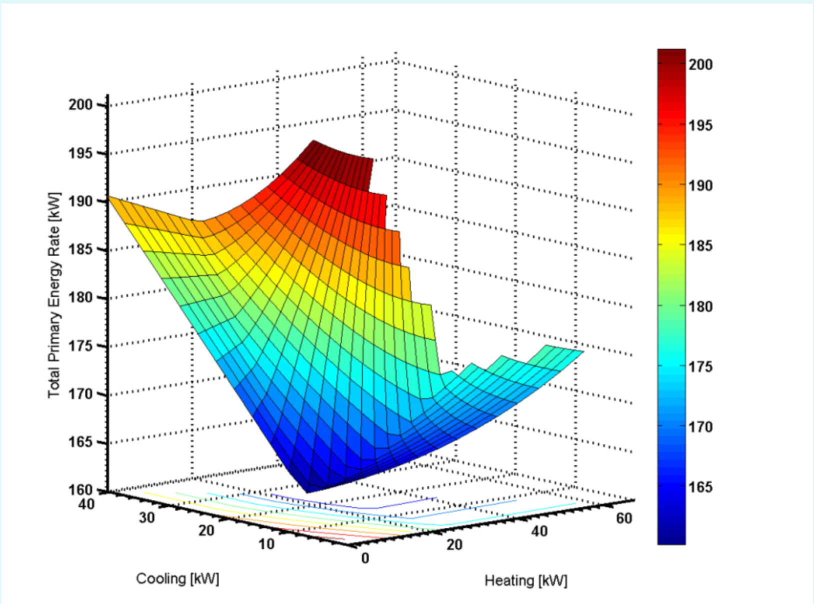
2b

Building Load Profile 2a:	**Mild Summer**	**Comparison**
Cooling Load	25 kW (85 kBtu/h)	*Grid Efficiency 33%*
Heating Load	0 kW	
Electrical Load	50 kW	
Building Load Profile 2b:	**Mild Summer**	**Comparison**
Cooling Load	25 kW (85 kBtu/h)	*Grid Efficiency 38%*
Heating Load	0 kW	
Electrical Load	50 kW	

Variation in Electrical Load



3a



3b

Building Load Profile 3a:	**Mixed**	**Comparison**
Cooling Load	25 kW (85 kBtu/h)	*Electric Load of 10 kW*
Heating Load	25 kW (85 kBtu/h)	
Electrical Load	10 kW	
Building Load Profile 3b:	**Mixed**	**Comparison**
Cooling Load	25 kW (85 kBtu/h)	*Electric Load of 50 kW*
Heating Load	25 kW (85 kBtu/h)	
Electrical Load	50 kW	

Main Program Computation Time

Profiler

File Edit Debug Desktop Window Help

Start Profiling Run this code: Profile time: 3 sec

3 seconds

Profile Summary

Generated 22-Jun-2011 17:58:35 using cpu time.

Function Name	Calls	Total Time	Self Time*	Total Time Plot (dark band = self time)
Abs_Ch_Reverse_V2	2	1.911 s	0.030 s	
mupadmex (MEX-file)	52	1.631 s	1.631 s	
solve	2	1.101 s	0.000 s	
Read_input_file_variables	1	0.891 s	0.010 s	
xlsread	1	0.881 s	0.280 s	
solve>getEqns	2	0.871 s	0.110 s	
sym.subs	2	0.781 s	0.010 s	
sym.subs>mupadsubs	2	0.761 s	0.010 s	
sym.subs>tryFunctionHandle	2	0.751 s	0.000 s	
sym.char	2	0.650 s	0.000 s	
actxserver	1	0.550 s	0.550 s	
sym.sym>sym.mupadmexnout	2	0.230 s	0.000 s	
msgbox	1	0.170 s	0.110 s	
sym.sym>sym.transpose	2	0.060 s	0.000 s	
sym.subs>isValidBody	2	0.050 s	0.010 s	
cell.setdiff	2	0.040 s	0.020 s	
iofun\private\validpath	1	0.030 s	-0.000 s	

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Device Manager

Remote settings

System protection

Advanced system settings

View basic information about your computer

Windows edition

Windows 7 Professional

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Get more features with a new edition of Windows 7

System

Manufacturer:	Dell
Model:	Precision T5500
Rating:	5.9 Windows Experience Index
Processor:	Intel(R) Xeon(R) CPU E5504 @ 2.00GHz 2.00 GHz (2 processors)
Installed memory (RAM):	6.00 GB
System type:	64-bit Operating System
Pen and Touch:	No Pen or Touch Input is available for this Display

Plotting and Writing to File Time

Profiler

File Edit Debug Desktop Window Help

Start Profiling Run this code: Profile time: 7 sec

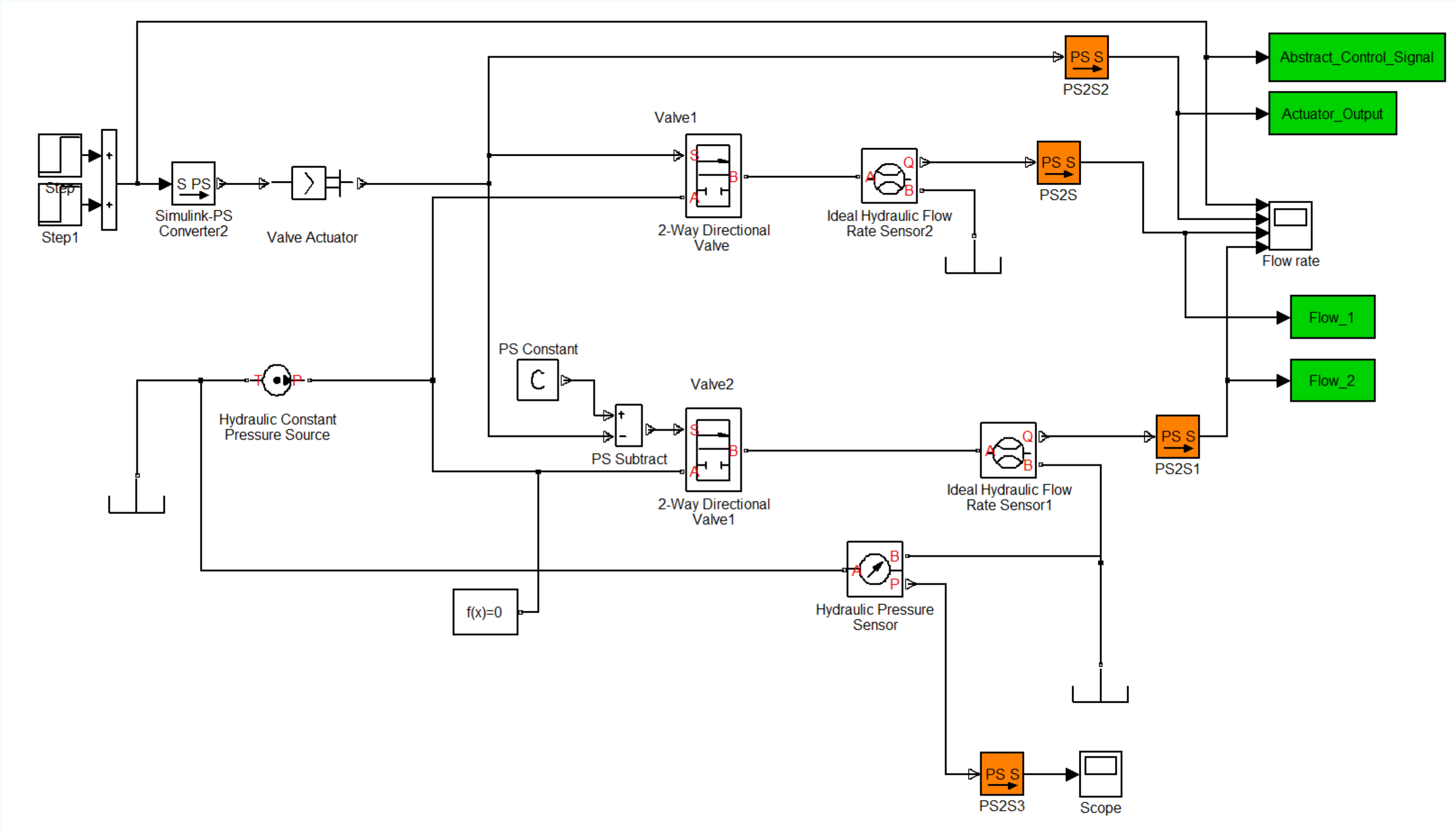
7 seconds

Profile Summary

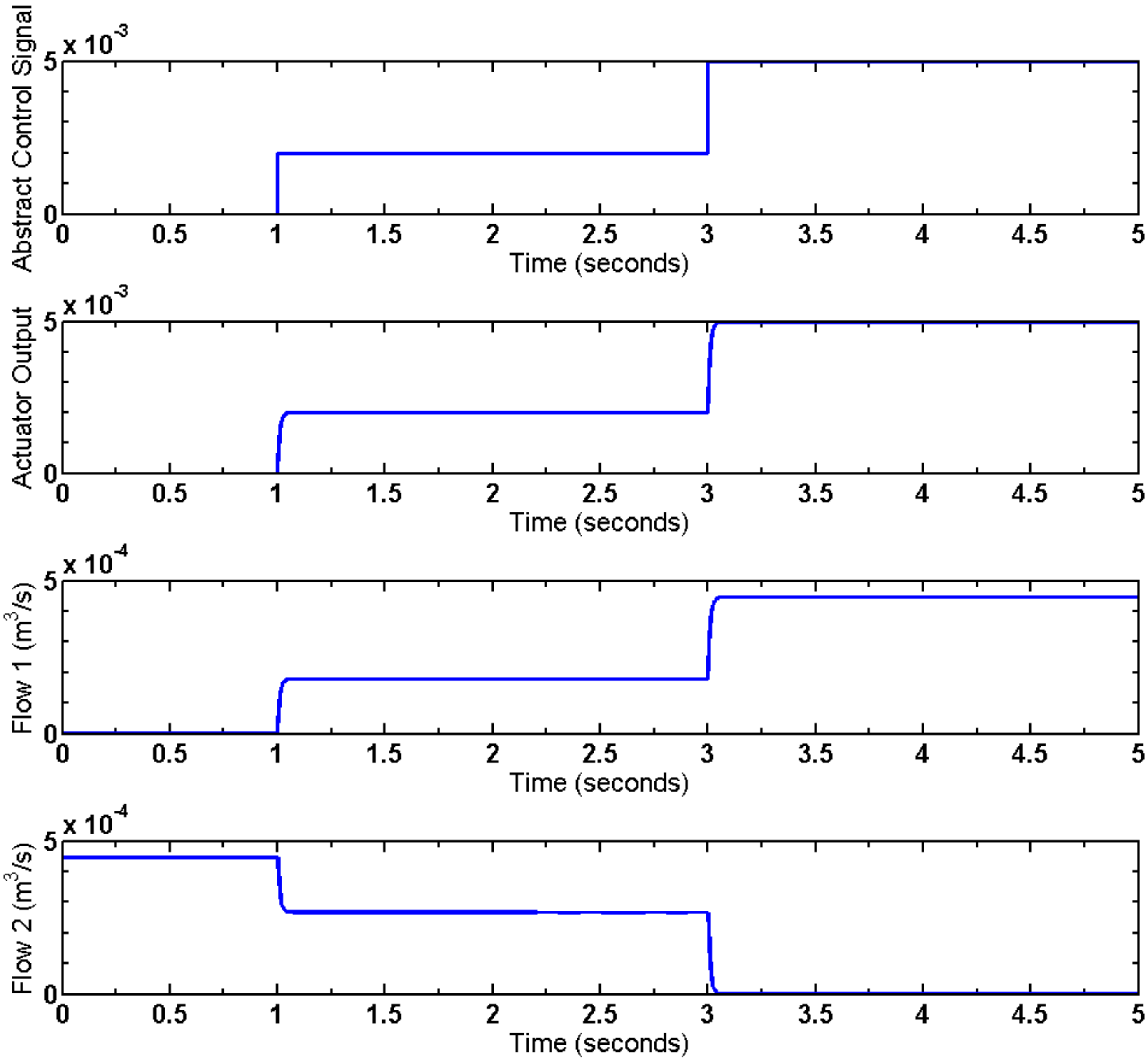
Generated 22-Jun-2011 18:14:10 using cpu time.

Function Name	Calls	Total Time	Self Time*	Total Time Plot (dark band = self time)
print	4	3.229 s	0.080 s	
legendcolorbarlayout>doLayout	174	1.720 s	0.160 s	
graphics\private\prepare	4	1.560 s	0.270 s	
legendcolorbarlayout>doLayoutCB	190	1.250 s	0.080 s	
scribe.legend.methods	180	1.070 s	0.030 s	
xlswrite	1	1.040 s	0.010 s	
legendcolorbarlayout>doInOutLayout	174	0.970 s	0.040 s	
graphics\private\render	4	0.880 s	0.010 s	
legendcolorbarlayout>doParentResize	16	0.830 s	0.050 s	
scribe.legend.methods>getsizeinfo	131	0.750 s	0.120 s	
legend	3	0.740 s	0.040 s	
scribe.legend.methods>getsize	131	0.730 s	0.030 s	
legend>make_legend	3	0.700 s	0.010 s	
scribe.legend.methods>strsize	1046	0.620 s	0.560 s	
scribe.legend.legend	3	0.600 s	0.090 s	
hardcopy	4	0.600 s	0.190 s	
graphics\private\preparehg	4	0.540 s	0.030 s	
actxserver	1	0.510 s	0.500 s	
xlswrite>ExecuteWrite	1	0.510 s	0.430 s	
...be.legend.methods>create_legend_items	3	0.490 s	0.060 s	
graphics\private\fireprintbehavior	8	0.390 s	0.060 s	
graphics\private\restore	4	0.390 s	0.010 s	
graphics\private\restorehg	4	0.380 s	0.080 s	
scribe.legend.init	3	0.370 s	0.070 s	
hggetbehavior	1966	0.340 s	0.140 s	
findobj	176	0.280 s	0.000 s	
findobjhelper	176	0.280 s	0.280 s	
ylabel	8	0.250 s	0.010 s	
colorbar	1	0.250 s	0.010 s	
legendcolorbarlayout>getPixelBounds	122	0.250 s	0.060 s	
scribe.colorbar.colorbar	1	0.240 s	0.040 s	
colorbar>make_colorbar	1	0.240 s	0.000 s	

Control of Three-Way Valve for Recovered Heat Distribution



Model Developed in SimHydraulics®



Abstract Control Signal
x 10^-3
5
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time (seconds)
Actuator Output
x 10^-3
Time (seconds)
Flow 1 (m^3/s)
x 10^-4
Time (seconds)
Flow 2 (m^3/s)
x 10^-4
Time (seconds)

Summary

- A detailed physical model of a CHP/thermally driven space conditioning system was implemented using MATLAB
- Optimum operating conditions (setpoints) could be computed for any specific load combinations and environmental conditions at intervals consistent with real time control
- Effectiveness of the method is highly dependent on the accuracy of the component models and the measured data
- Currently adding more detailed models of system components and auxiliaries
- Method could be applied to other system configurations and designs

Questions?

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