From Buildings to Cities:
Research and Development of Modelica-based Technique for Real-world Applications

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11/15/2016

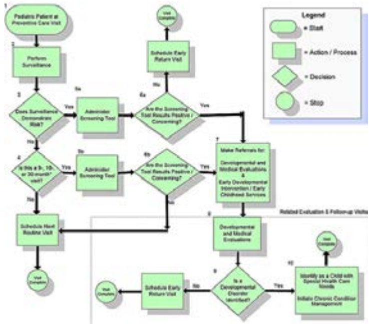
Presentation at Lawrence Berkeley National Laborator

Outline

- **Brief Introduction of Modelica**
- **Real-World Applications:**
  - Modeled-based Chilled Water Plan Optimization
  - Energy and Water Efficient Hotel
  - Net Zero Energy Community
- **Conclusion and Future Research:**
  - Energy Efficient Data Center Cooling
  - Smart and Connected Community
  - Resilient Coast City Design

Conventional Building Modeling and Simulation

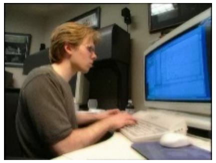
$$\mathrm{COP}_{\mathrm{nominal}} = \frac{\mathrm{etaCar} \cdot \mathrm{TEva}_{\mathrm{nominal}}}{\mathrm{TCon}_{\mathrm{nominal}} - \mathrm{TEva}_{\mathrm{nominal}}}$$



Physical Equipment

Physical Models

Numerical Algorithms

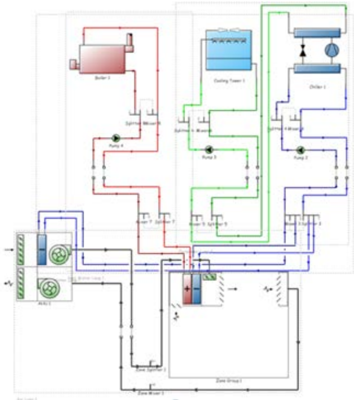


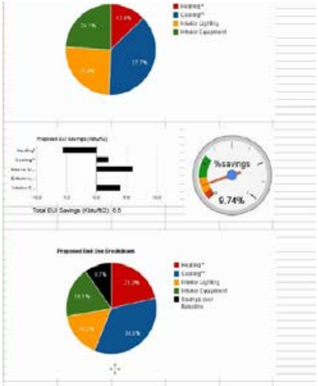
```
// Declare local variable holding
int iErr;

// *** Declare and initialize inp
// *** passed into the NAG functi
int nPts;         // Input number
int nTdx;         // Input number
matrix mX;        // Input matrix
vector vY;        // Input vector
vector vWT;       // Input vector

// There are 10 rows of data in s
nPts = 10;

// There are 3 independent variab
nTdx = 3;
```





Results

System Model

Code

Equation-Based Modeling Language

Can you write a C code to solve these equations in 1 minutes?

$$(1 + 0.5\sin(y))\frac{dx}{dt} + \frac{dy}{dt} = \mathrm{a}\sin(t)$$

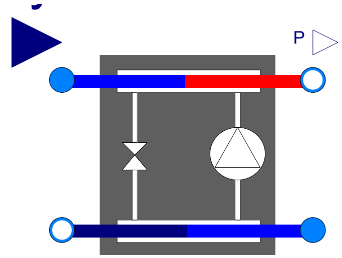
$$x - y = e^{-0.9x}\cos(y)$$

You can do it using equation-based modeling language in 1 minute:

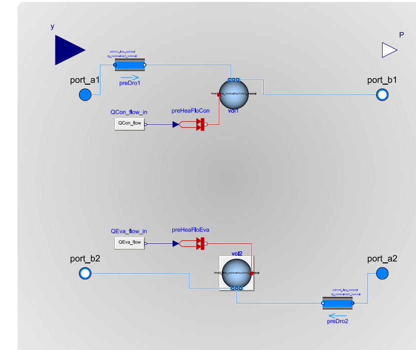
```
model DAEexample
Real x(start = 0.9,fixed=true);
Real y(fixed=false);
parameter Real a=2;
equation
(1 + 0.5*sin(y))*der(x) + der(y) = a*sin(time);
x-y = exp(-0.9*x)*cos(y);
end DAEexample;
```

Equation-Based Building Modeling and Simulation

Physical Equipment



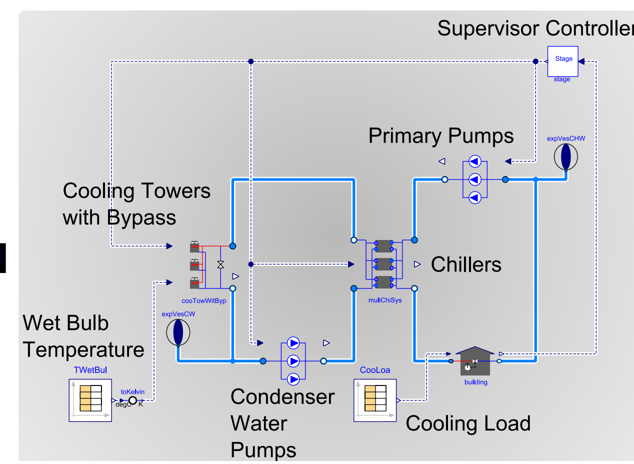
Physical Models



Diagram

$$COP_{nominal} = \frac{etaCar \cdot TEva_{nominal}}{TCon_{nominal} - TEva_{nominal}}$$

Equation



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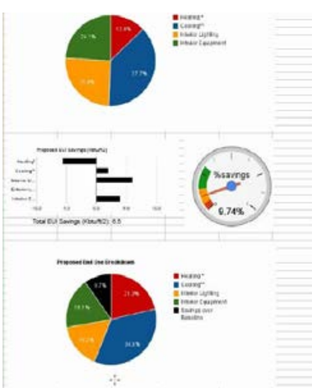
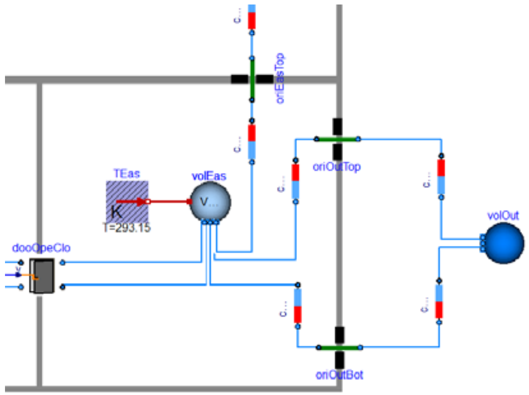
Code

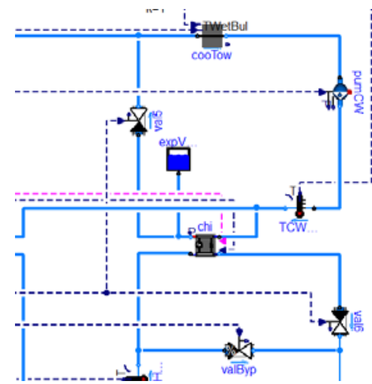


Results

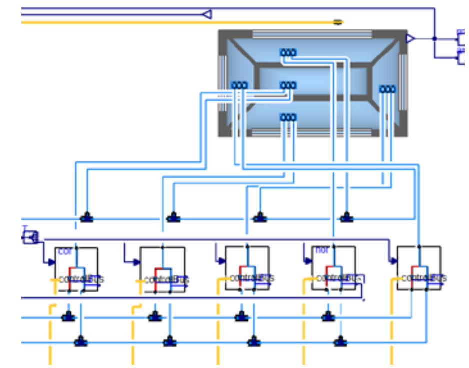
Modelica *Buildings* Library



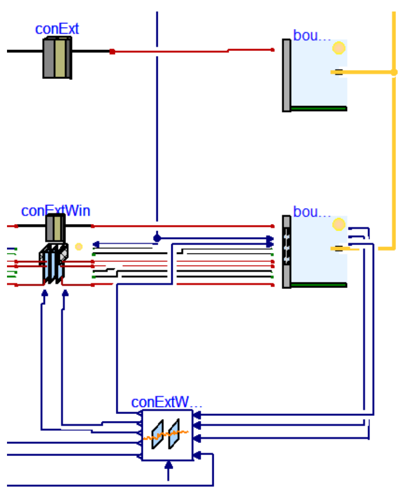
Airflow Network



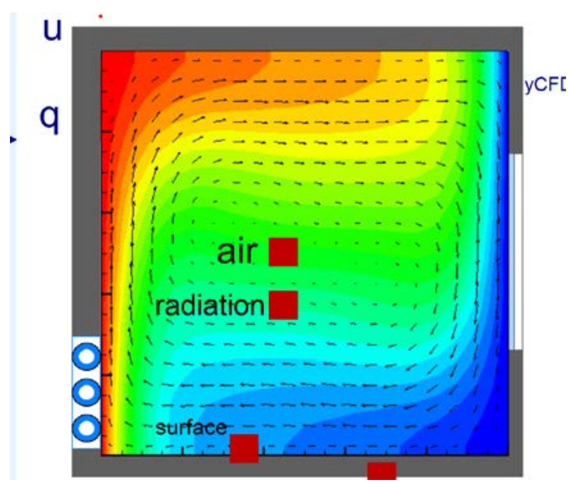
Water-Based HVAC System



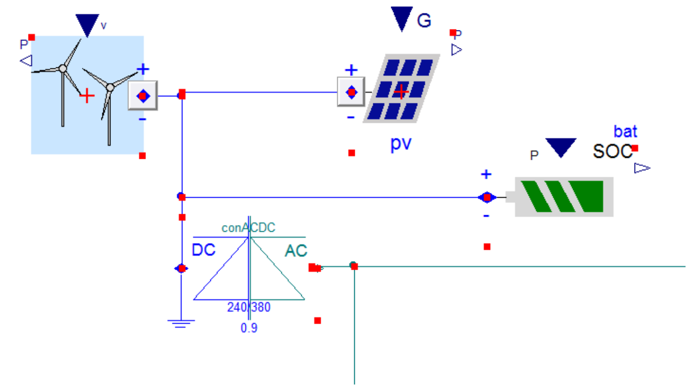
Air-Based HVAC System



Building Envelope



CFD



Renewable Generation

http://simulationresearch.lbl.gov/modelica

Wetter, Zuo, Nouidui, Pang, 2014, Journal of Building Performance Simulation;
Zuo, Wetter, Tian, Li, et al, 2015, Journal of Building Performance Simulation;

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Optimal Control for Chilled Water Plants

In FY 2012, Department of Defense spent **$3.8 billion** to power, heat and cool buildings (DoD 2013).

DoD ESTCP Project: Optimization operation efficiency: Integrating energy information systems (EIS) and model-based diagnostics

Period: 2012-2016

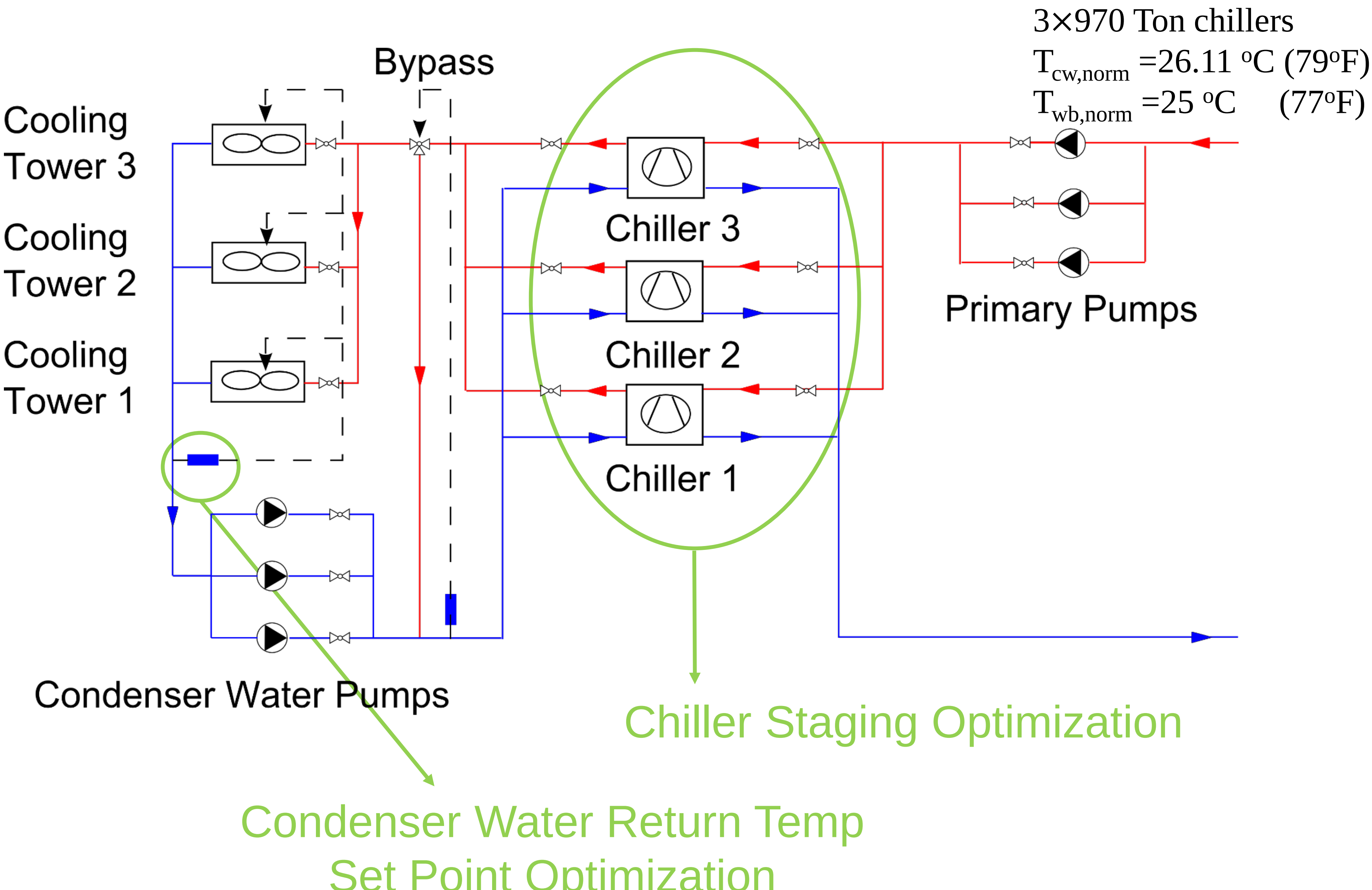
Project Team:

- Lawrence Berkeley National Lab
- University of Miami
- IBM

Project Site:

- Washington Navy Yard
- US Naval Academy

Studied Chiller Plant



Huang, Zuo, Sohn 2016, Applied Energy
Huang, Zuo, Sohn 2017, Building and Environment

Condenser Water Return Temp Set Point Optimization

$$\min\left(OB|_{t_0}^{t_0+\Delta t}\right) = \min\left(\int_{t_0}^{t_0+\Delta t} f_1\left(\overrightarrow{OP}(t_0), \overrightarrow{IP}(t), \vec{S}(t_0)\right)\right) \text{ for } t \in [t_0, t_0+\Delta t)\,,$$

subject to $\overrightarrow{OP}(t_0) \in OP_{valid}$

$$f_2\left(\overrightarrow{OP}(t_0), \overrightarrow{IP}(t), \vec{S}(t_0)\right) = 0$$

$$f_3\left(\overrightarrow{OP}(t_0), \overrightarrow{IP}(t), \vec{S}(t_0)\right) \le 0$$

$$OB|_{t_0}^{t_0+\Delta t} = E_{ch}|_{t_0}^{t_0+\Delta t} + E_{tw}|_{t_0}^{t_0+\Delta t},$$

$$\overrightarrow{OP}(t_0) = \{T_{cw,set}(t_0)\},$$

$$\overrightarrow{IP}(t) = \left\{\dot{Q}^P(t), T_{wb}^P(t)\right\},$$

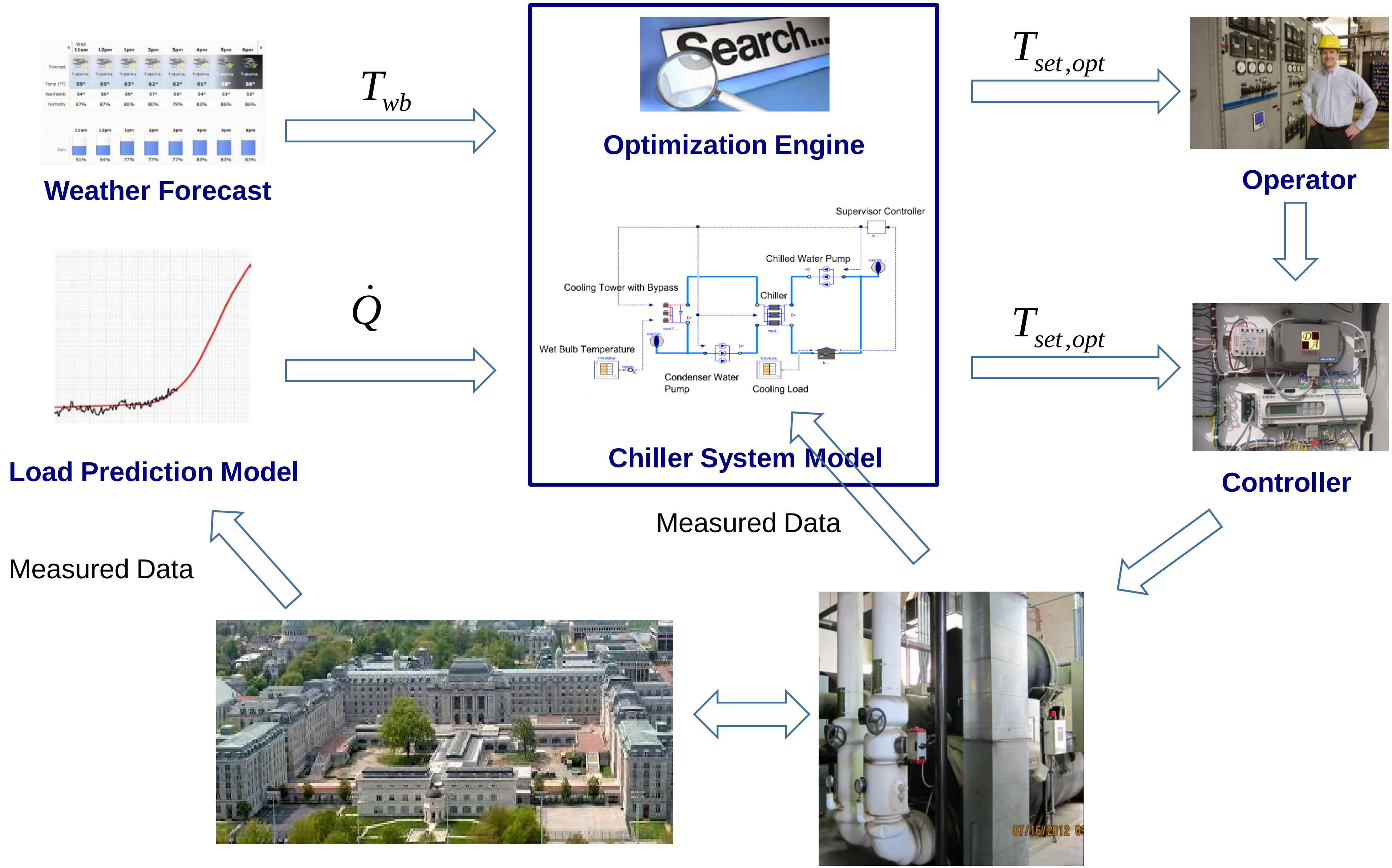
$$OP_{valid} = \left\{T_{cw,set} \middle| T_{cw,set,L} \le T_{cw,set} \le T_{cw,set,H}\right\},$$

Specialization for the condenser water return temp set point optimization

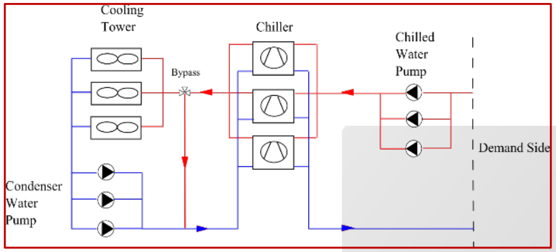
$T_{cw,set}$: condenser water return temp set point

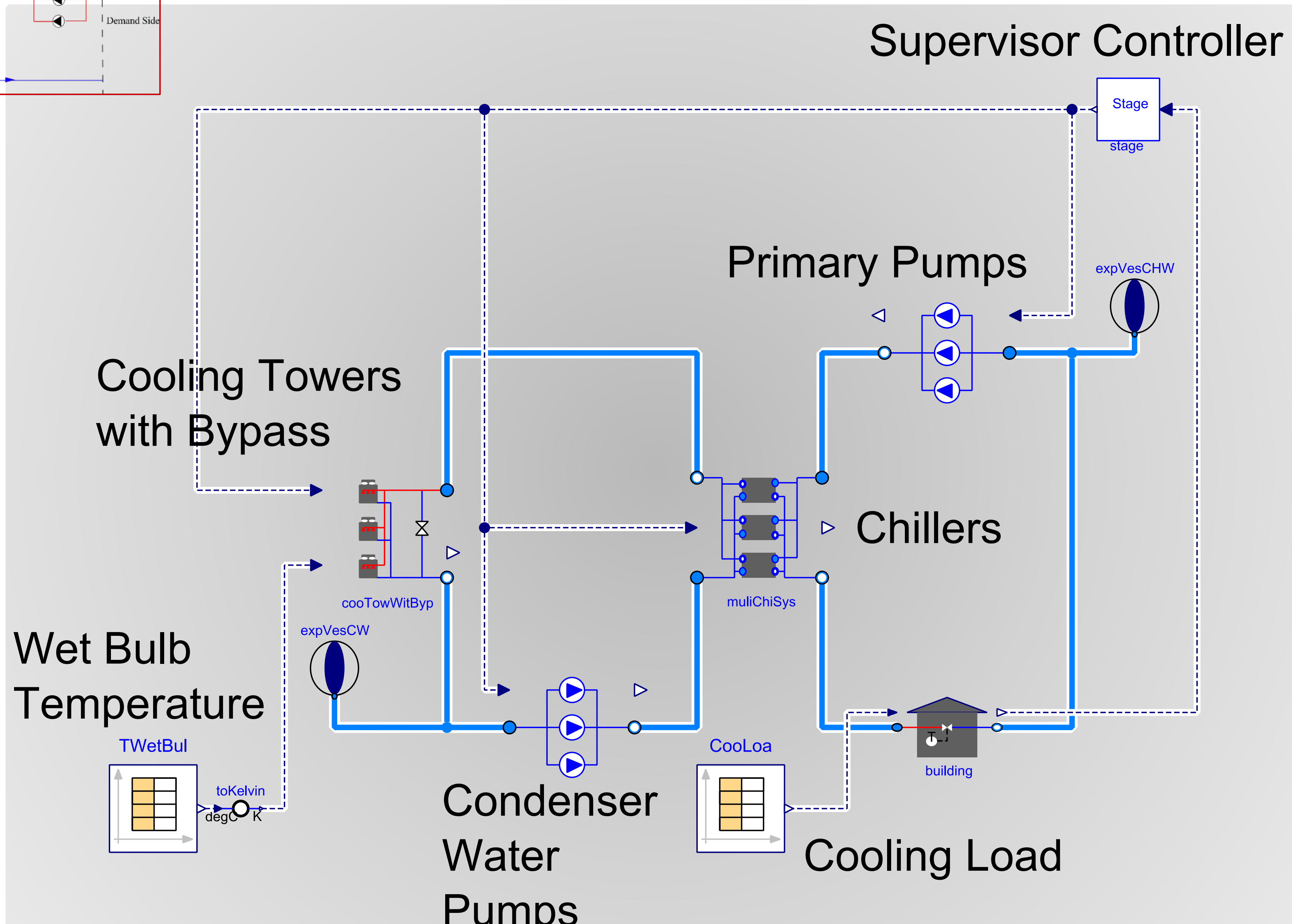
Q(t) : cooling energy demand

Work Flow of Model Predictive Control for Chillers

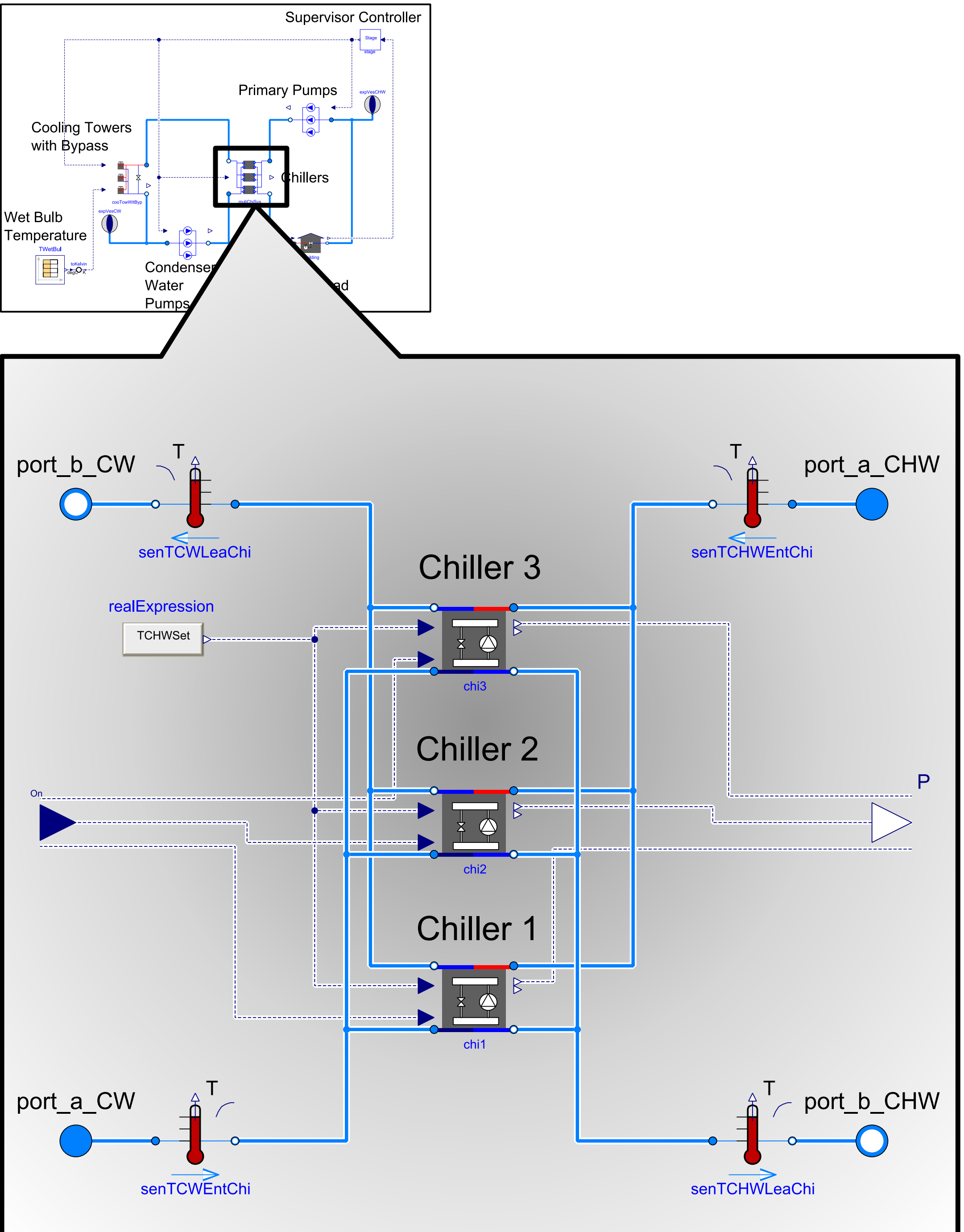


Simulation Model: System Level

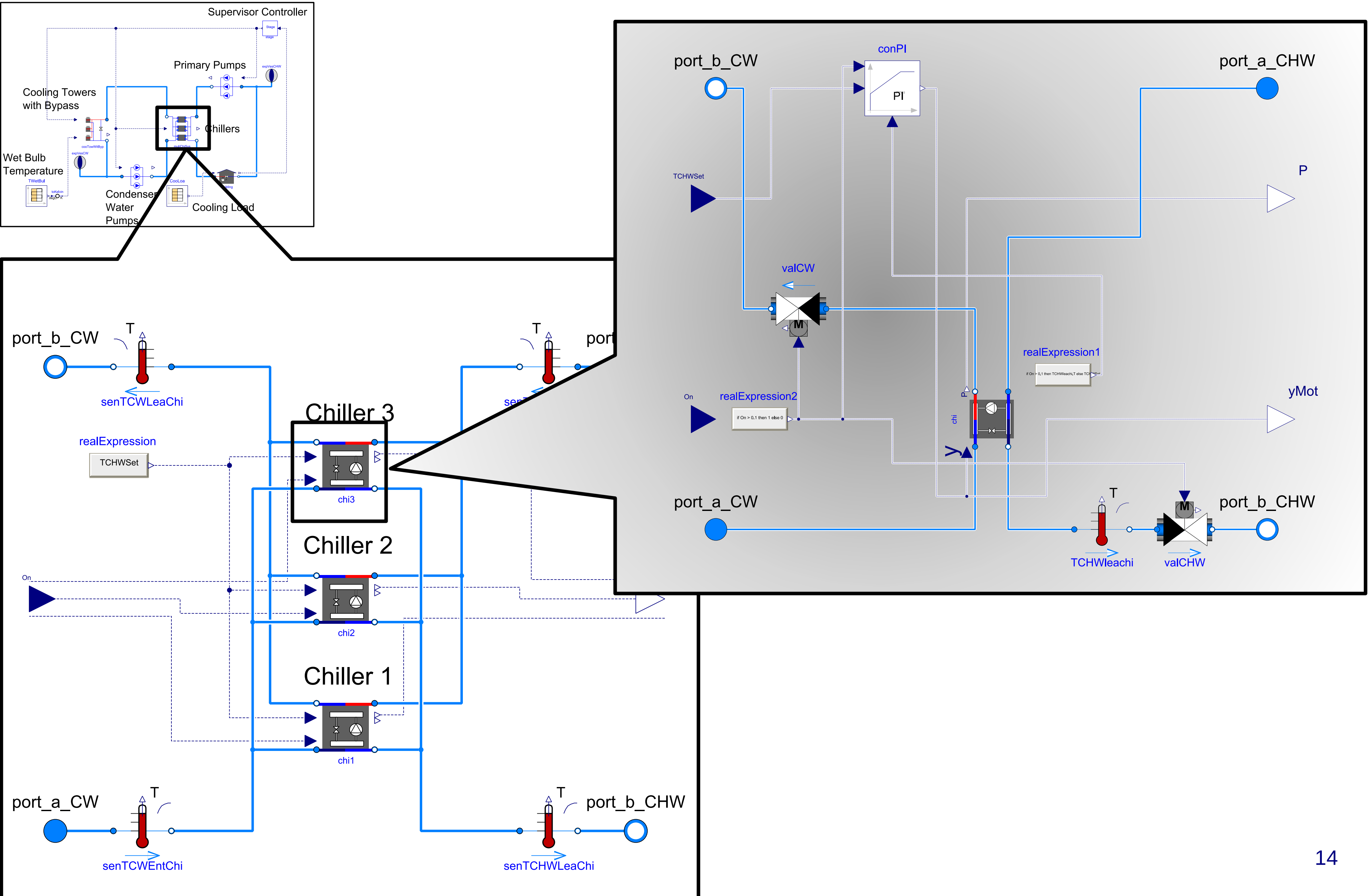




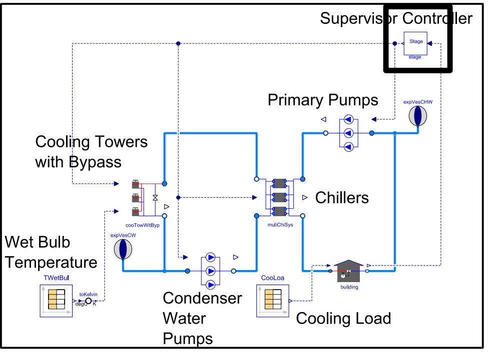
Simulation Model: Chiller Subsystem

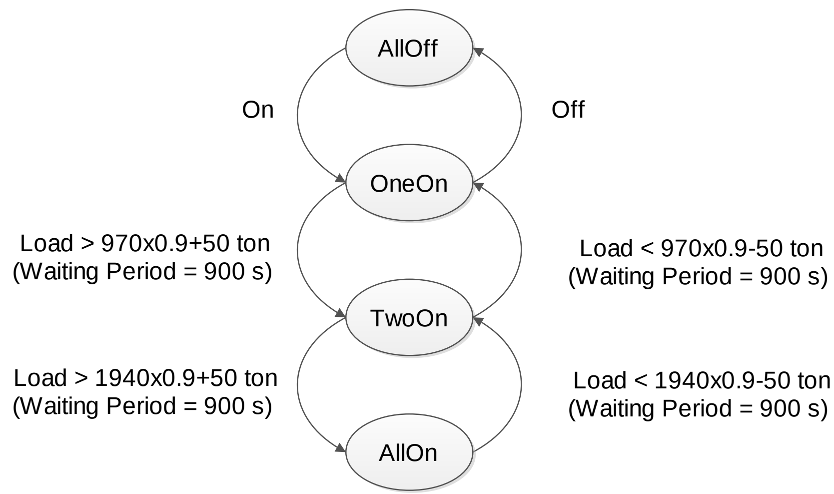


Simulation Model: Chiller Subsystem

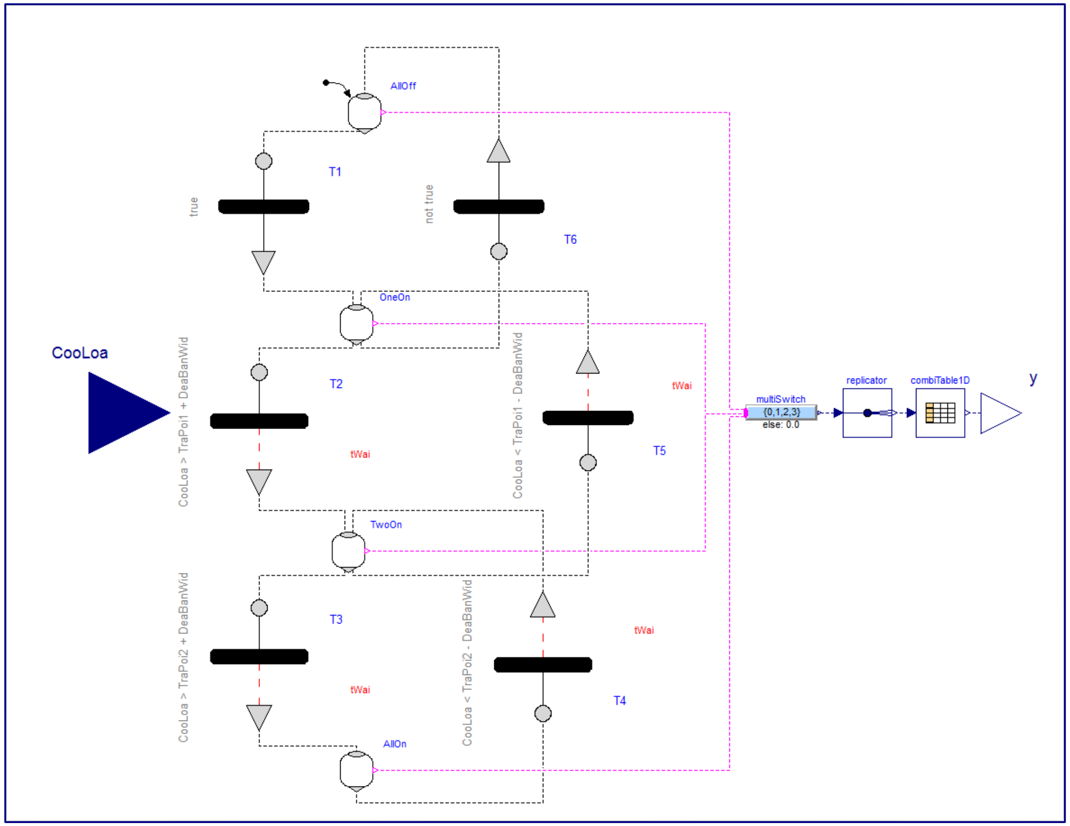


Simulation Model: Supervisory Control





State Machine



Modelica Model

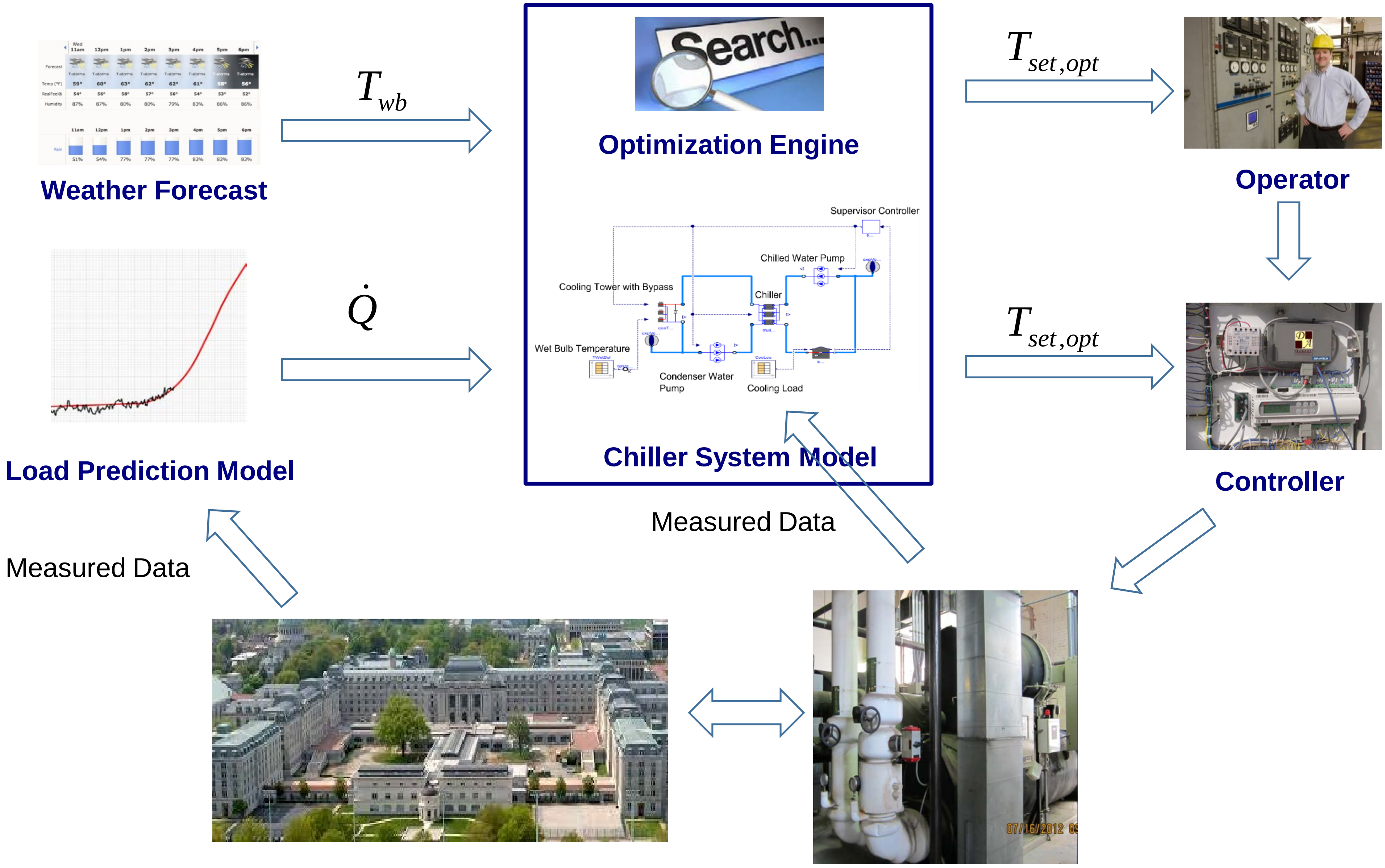
Energy Saving Potential

Optimization Methods	Energy Saving w. Faulty Tower	Energy Saving w. Normal Tower	Computing Hours
Hourly Exhaustive Search	1.76%	10.04%	33.7
Hourly GPS	1.74%	10.02%	23.8
Daily GPS	1.14%	9.49%	1.2
Energy Saving	64-99 MWh	483-511 MWh	
Cost Saving	$8,320-$12,870	$62,790-$66,430	

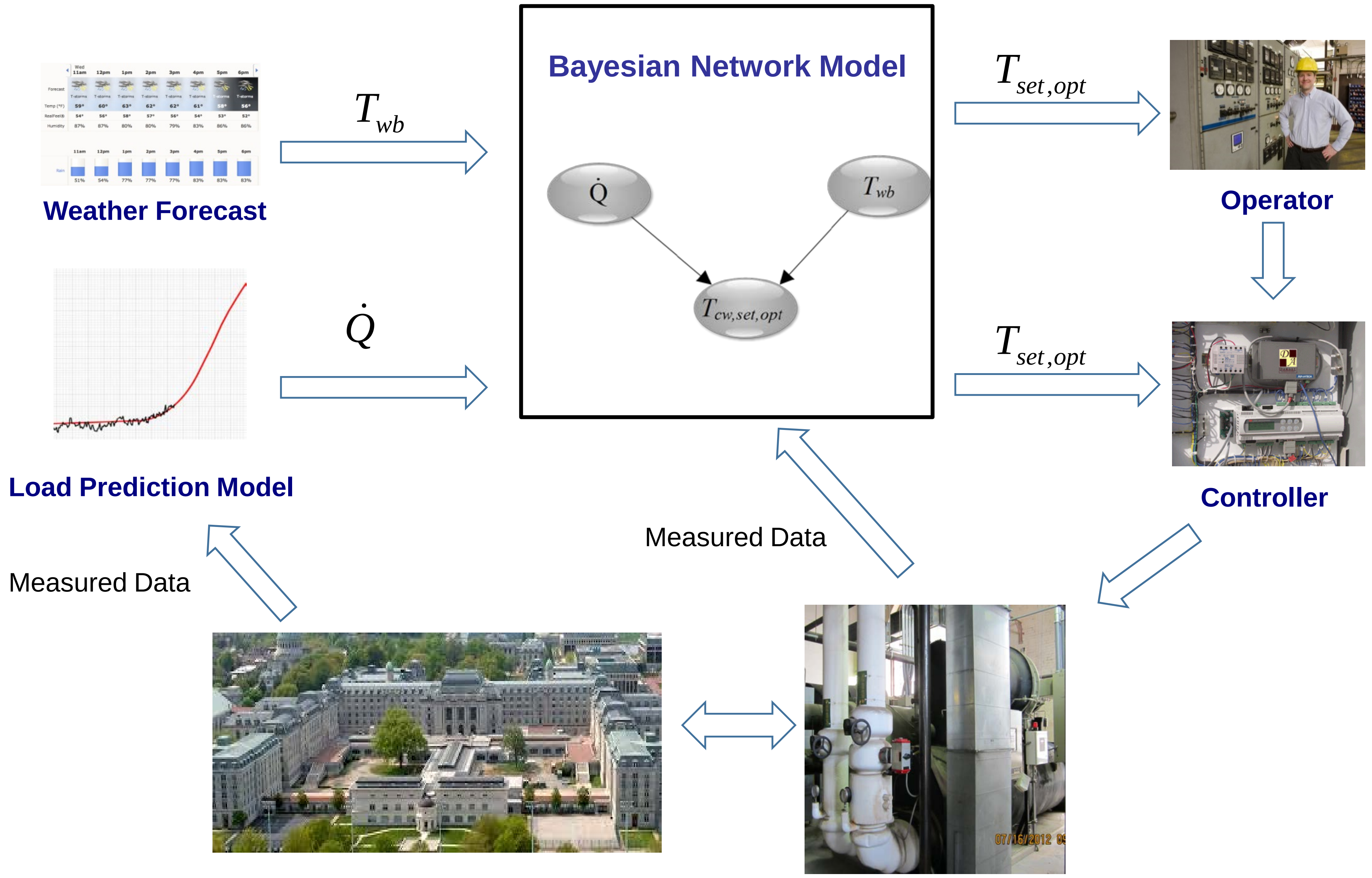
GPS: Hooke Jeeves Generic Pattern Search

Huang and Zuo, 2014, ASHRAE/IBPSA-USA Conference;
Huang, Zuo and Sohn, 2015, Building Simulation Conference;
Huang, Zuo and Sohn, 2016, Journal of Applied Energy

Optimization Based on Physical Model

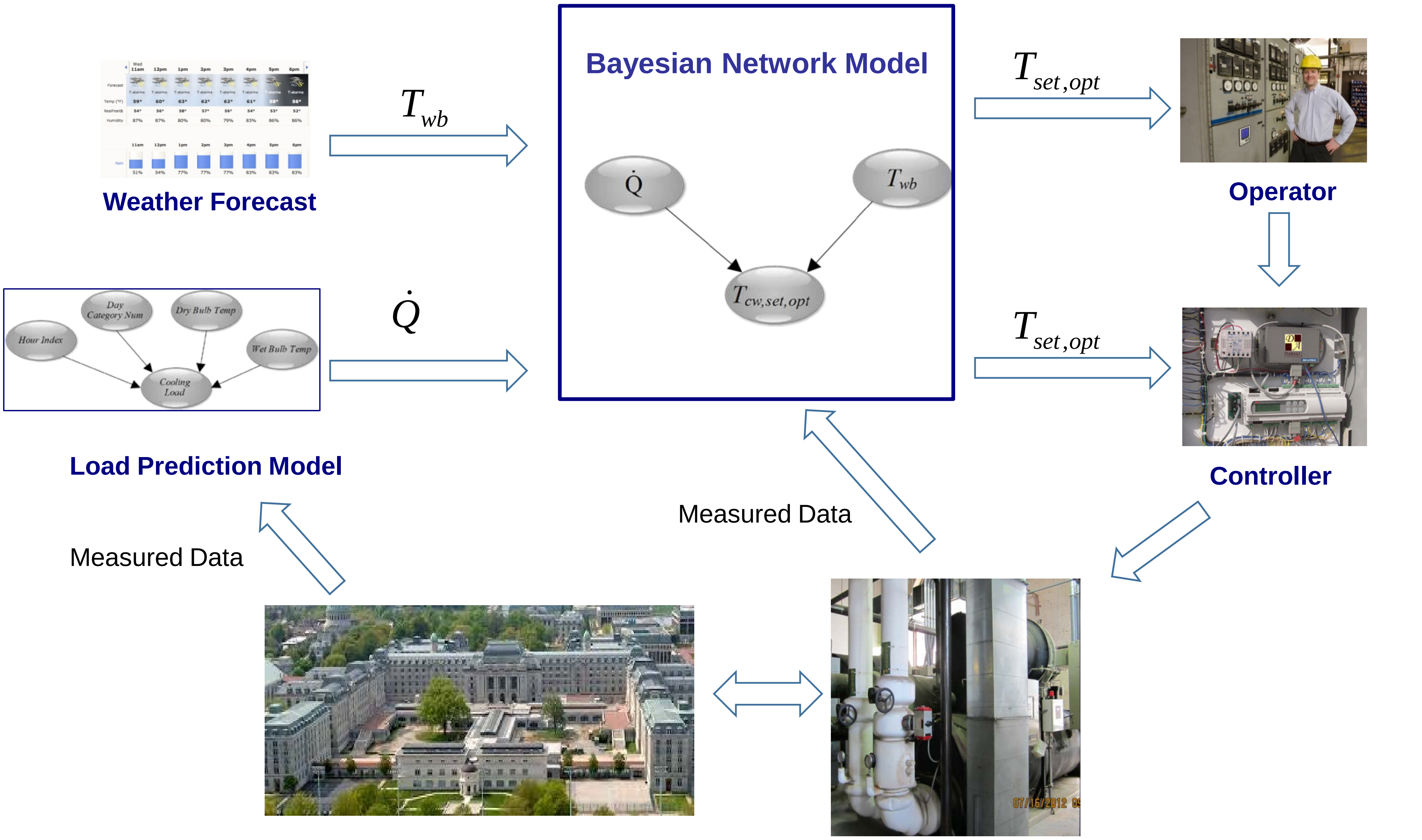


Optimization Based on *Regression* Model



Huang, Zuo, Sohn, 2015, Building Simulation Conference
Huang, Zuo, Sohn, 2016, SimBuild Conference

Optimization Based on *Regression* Model



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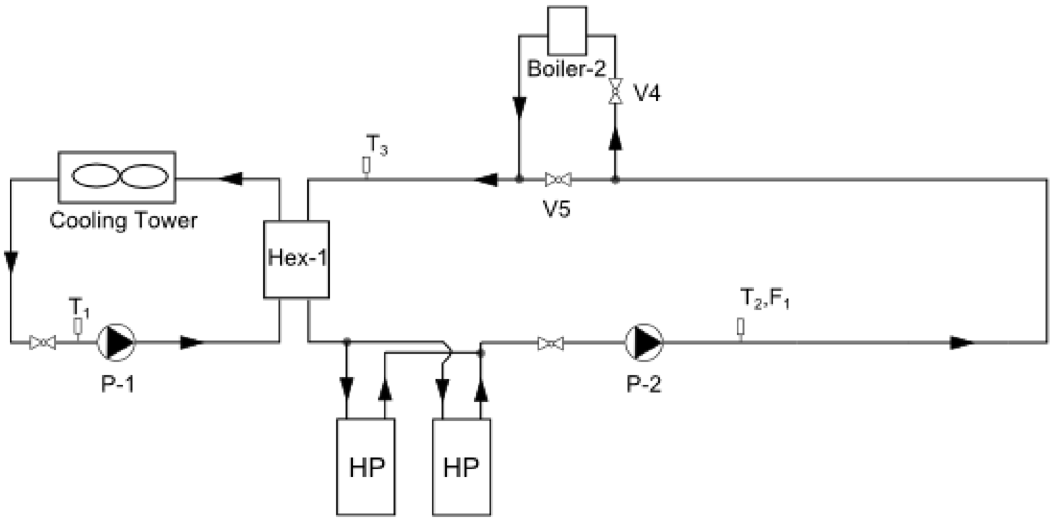
Energy and Water Efficient Hotel

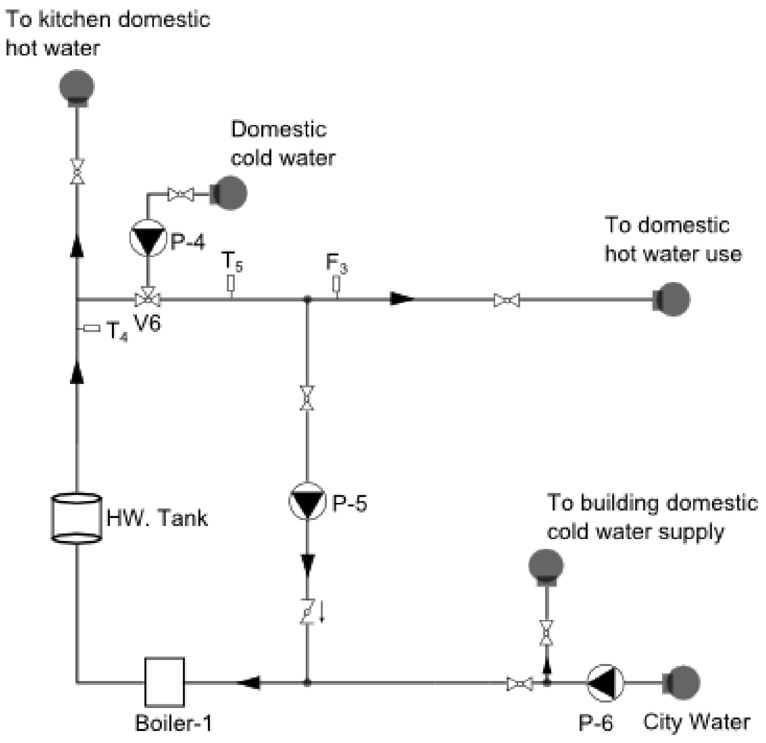
Grand Beach Hotel, Surfside, Miami Beach, FL, USA

Convectional System

Heat Pump for Space Cooling and Heating



Domestic Hot Water System

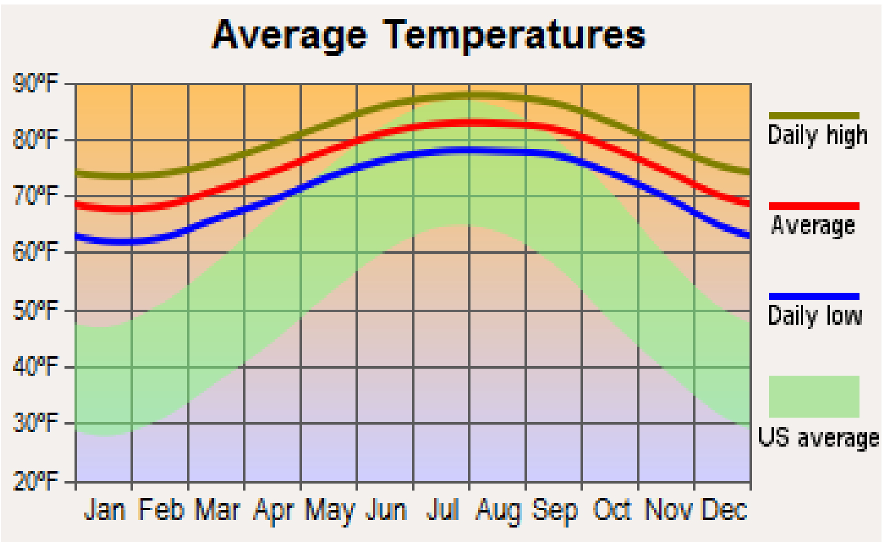


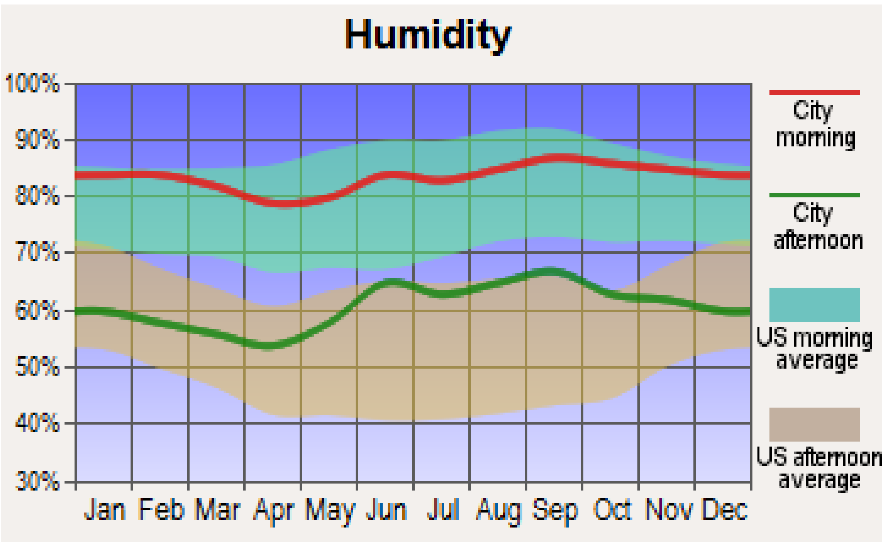
Weather in Miami

Miami, US:
ASHRAE Climate Zone 1A (Hot and Humid)

32.2°C

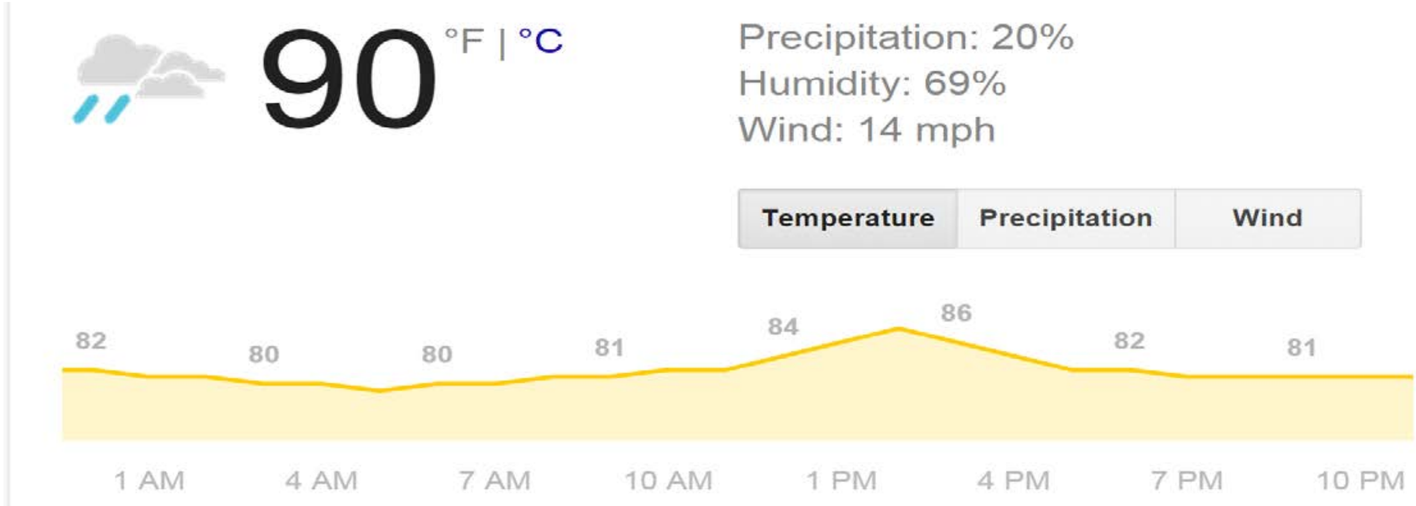
15.5°C



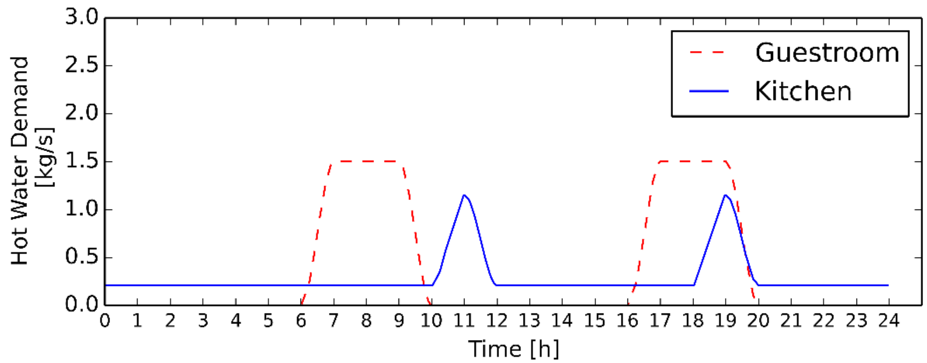


Cooling Demands vs Hot Water Demands

Typical Day of Miami Weather



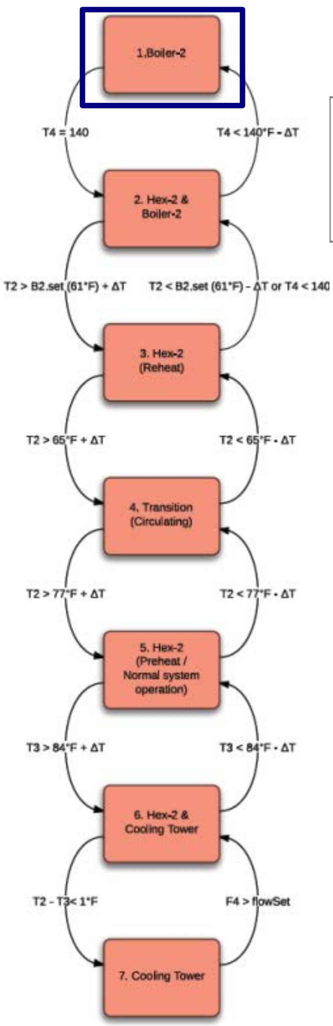
Typical Day of Hotel Guests

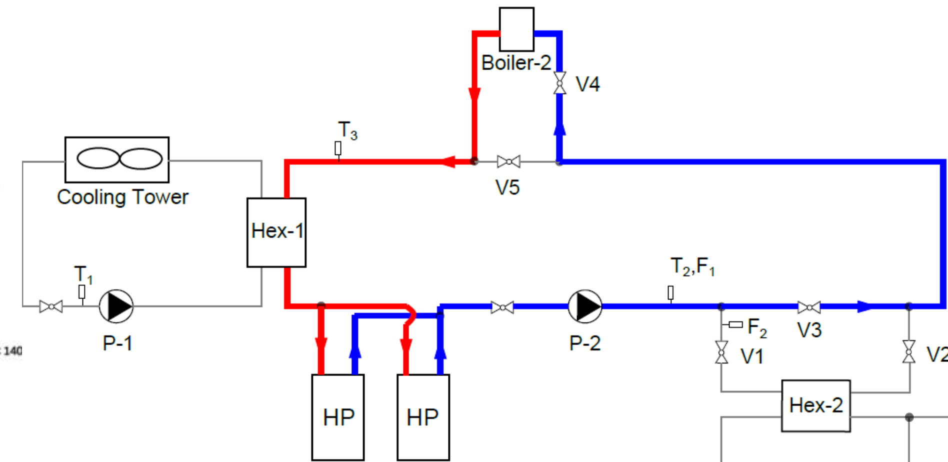


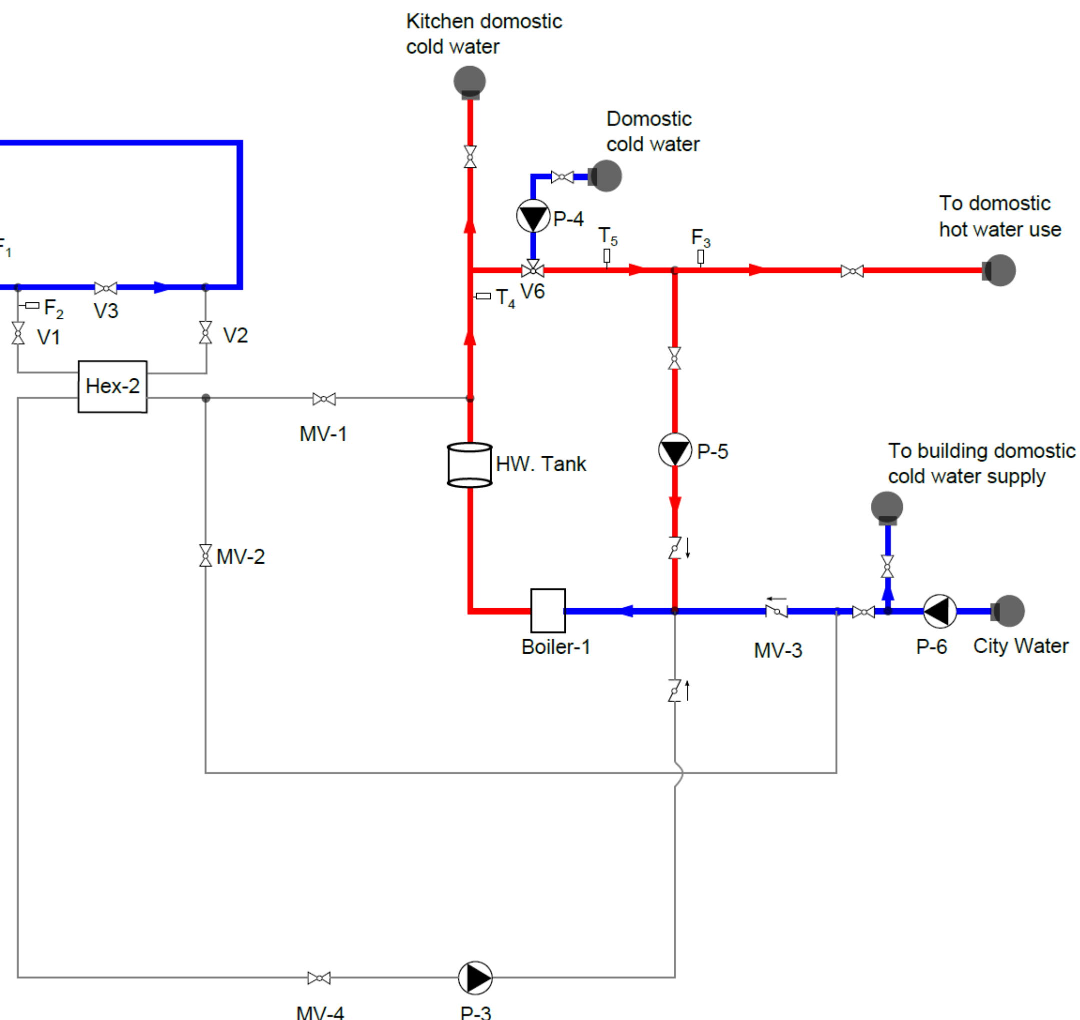
State 1: Large Demands for Heating and HW

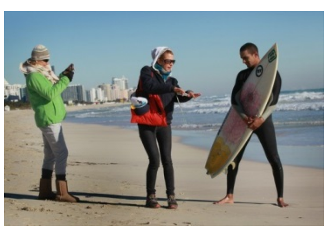
Heat Pump for Space Heating

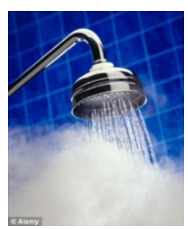
Heating for Domestic Hot Water











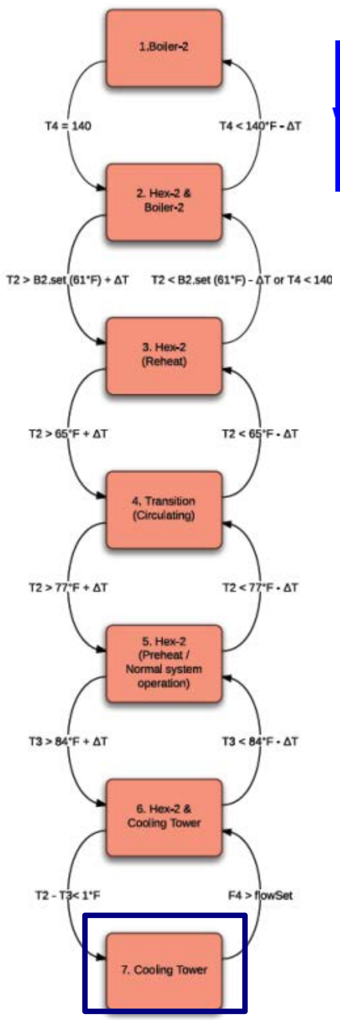
Sensors:
T: Temperature
F: Flow

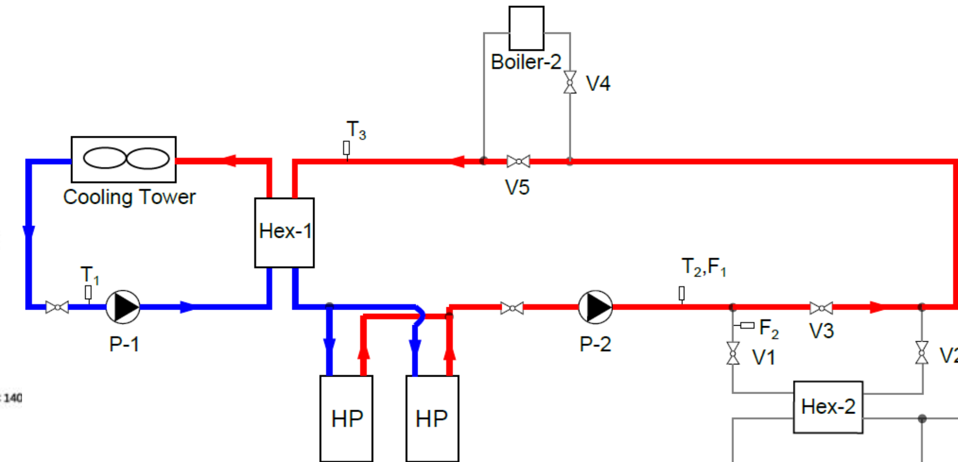
Equipments:
P: Pump
HP: Heat Pump
MV: Manual Valve
Hex: Heat Exchanger

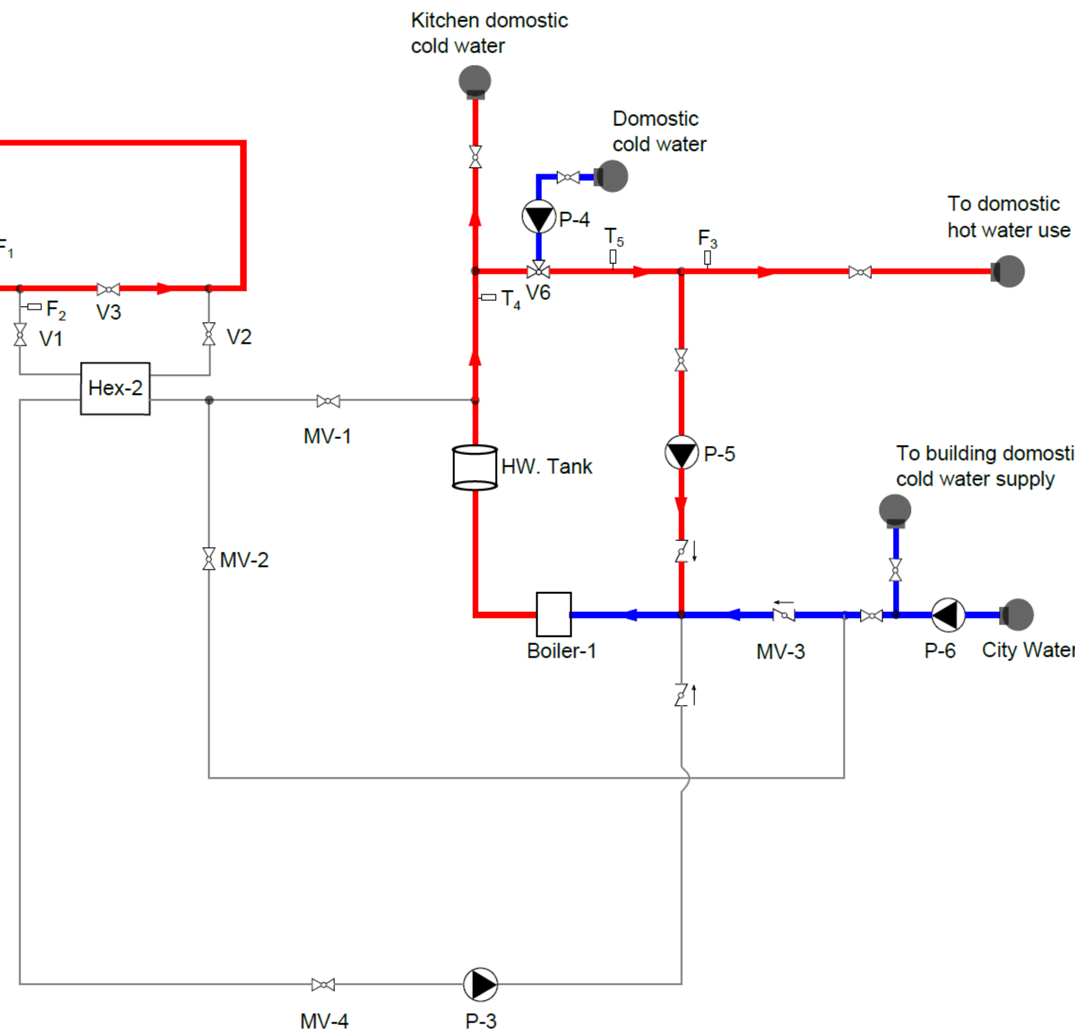
State 7: Demand Large for Cooling & Low for HW

Heat Pump for Space Cooling

Heating for Domestic Hot Water







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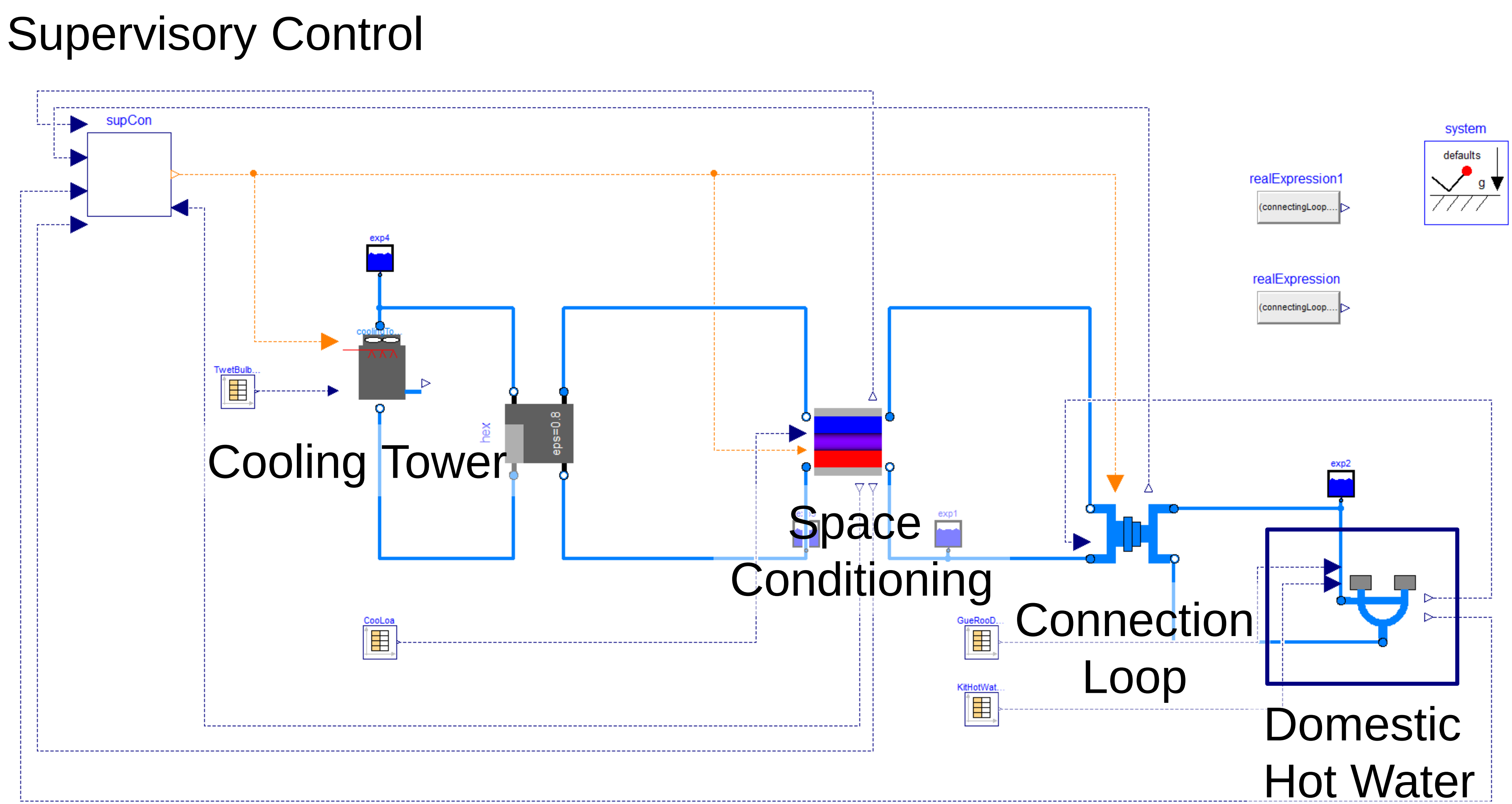
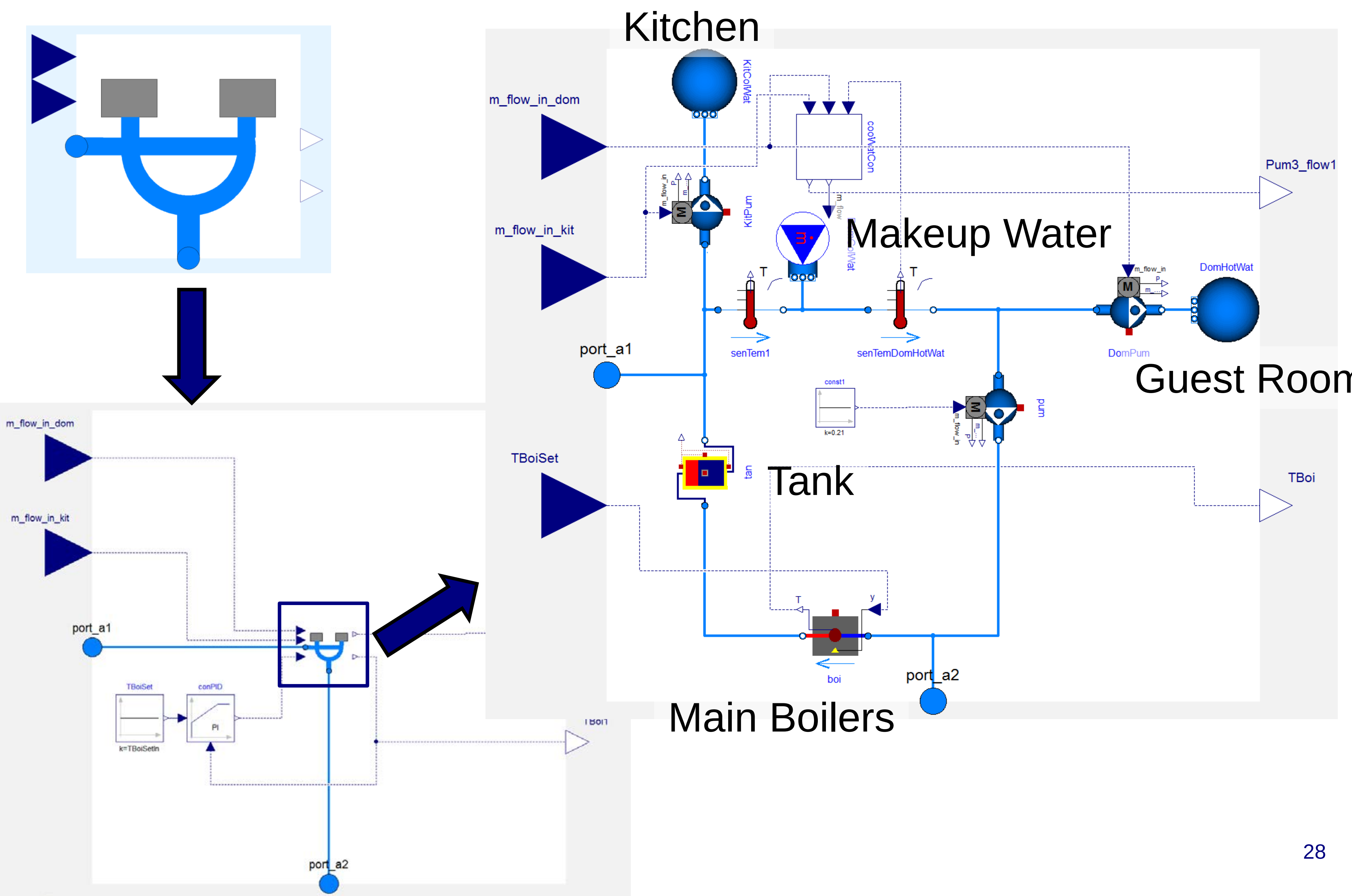
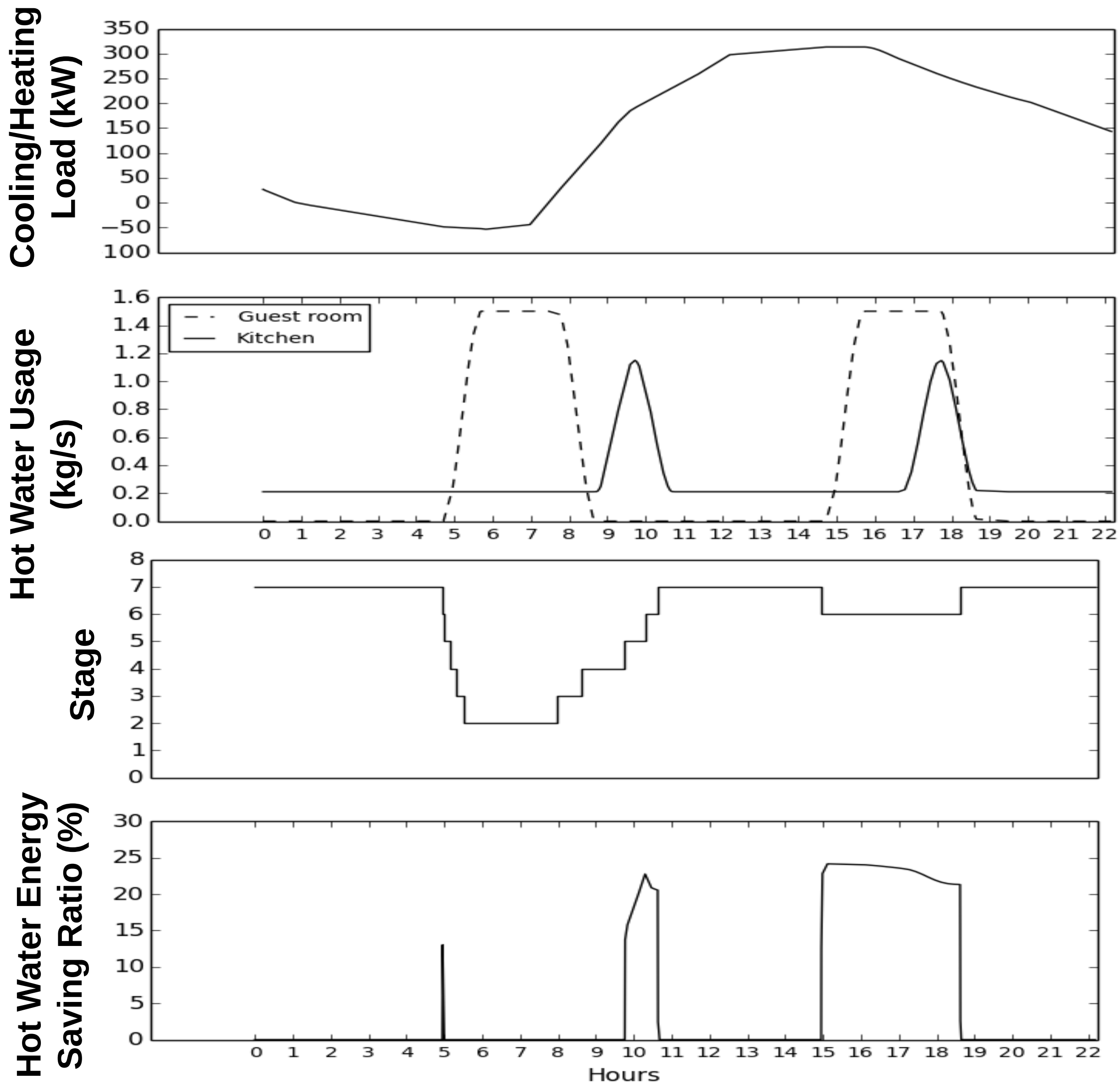
Heat Recovery System Model



Domestic Hot Water Sub-System Model



Preliminary Results: A Challenging Day

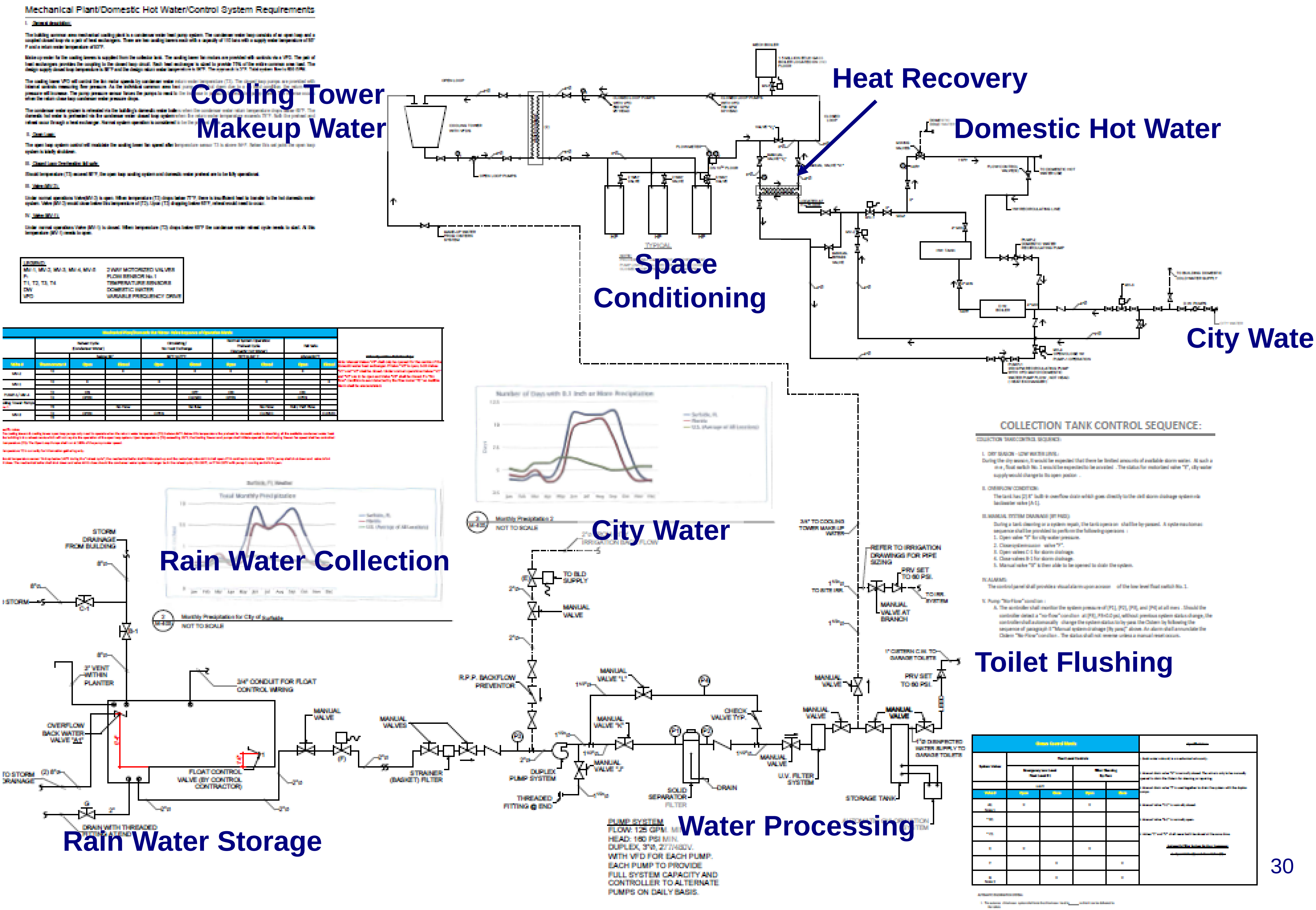


February 12th

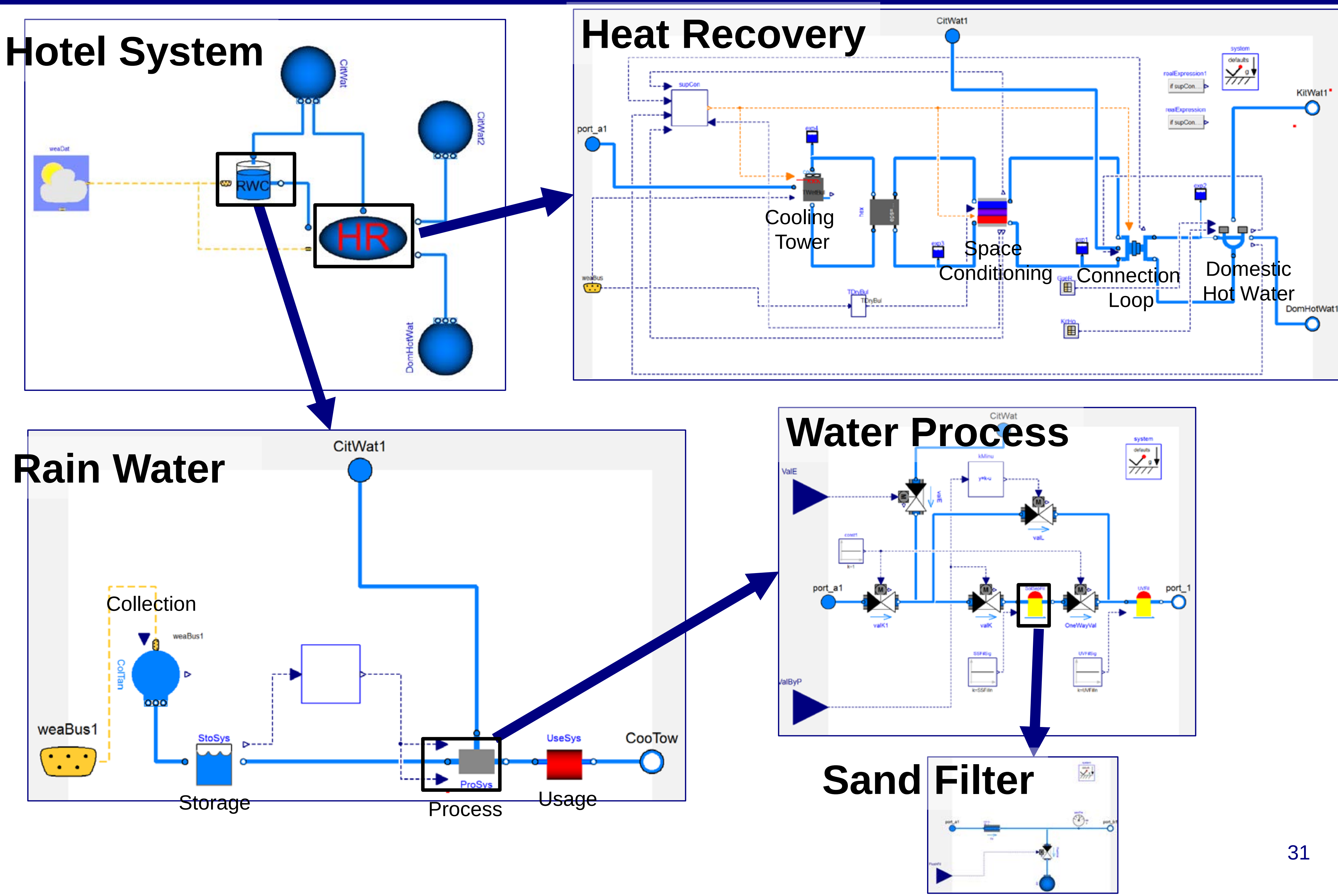
7: Cooling Tower Only
6: Heat Recovery + Cooling Tower
5: Heat Recovery Only
4: None
3: Main Boiler
2: Main Boiler + Auxiliary Boiler
1: Main Boiler, Auxiliary Boiler Separately

Miranda et al, 2015, Modelica Conference

Beyond Energy: Water



Modeling of Combined Energy and Water System



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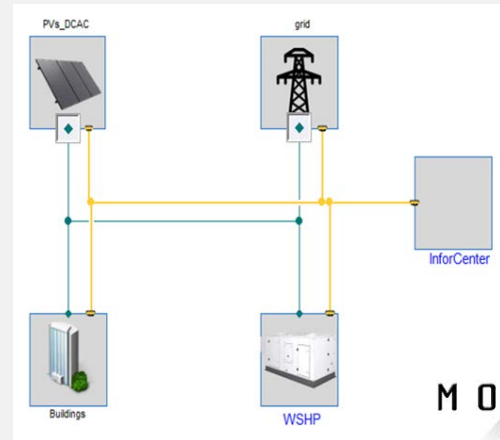
Smart and Sustainable Community Virtual Testbed

Community Data
Real Time & Historic

Smart & Sustainable Community Virtual Testbed

Buildings, Networks of Energy, Water & Transportation



MODELICA

Computational Models
Multiple Scales, Disciplines & Layers

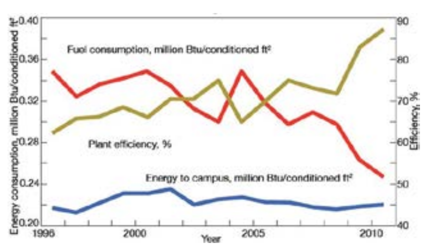
an engine for

Enhanced Situational Awareness

"What if" **Design** evaluation

Real-time **Operation** management

Smart Technologies



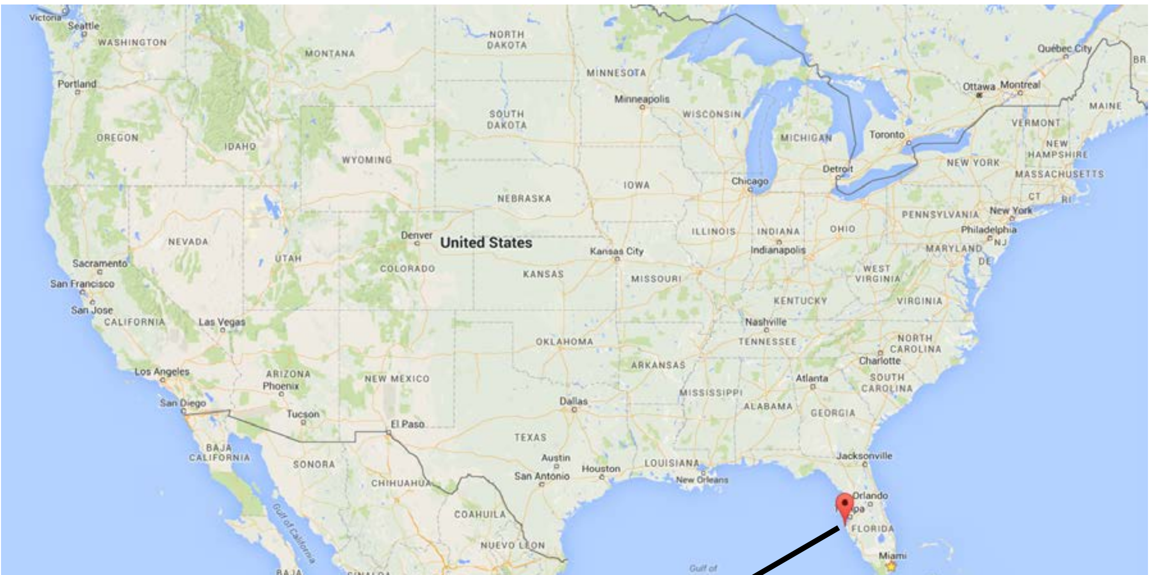
Economic & Cost

Model Predictive Control

Fault Detection and Diagnosis

Historic Green Village, Anna Maria Island, Florida

The Historic Green Village is an existing Net Zero Energy Community.



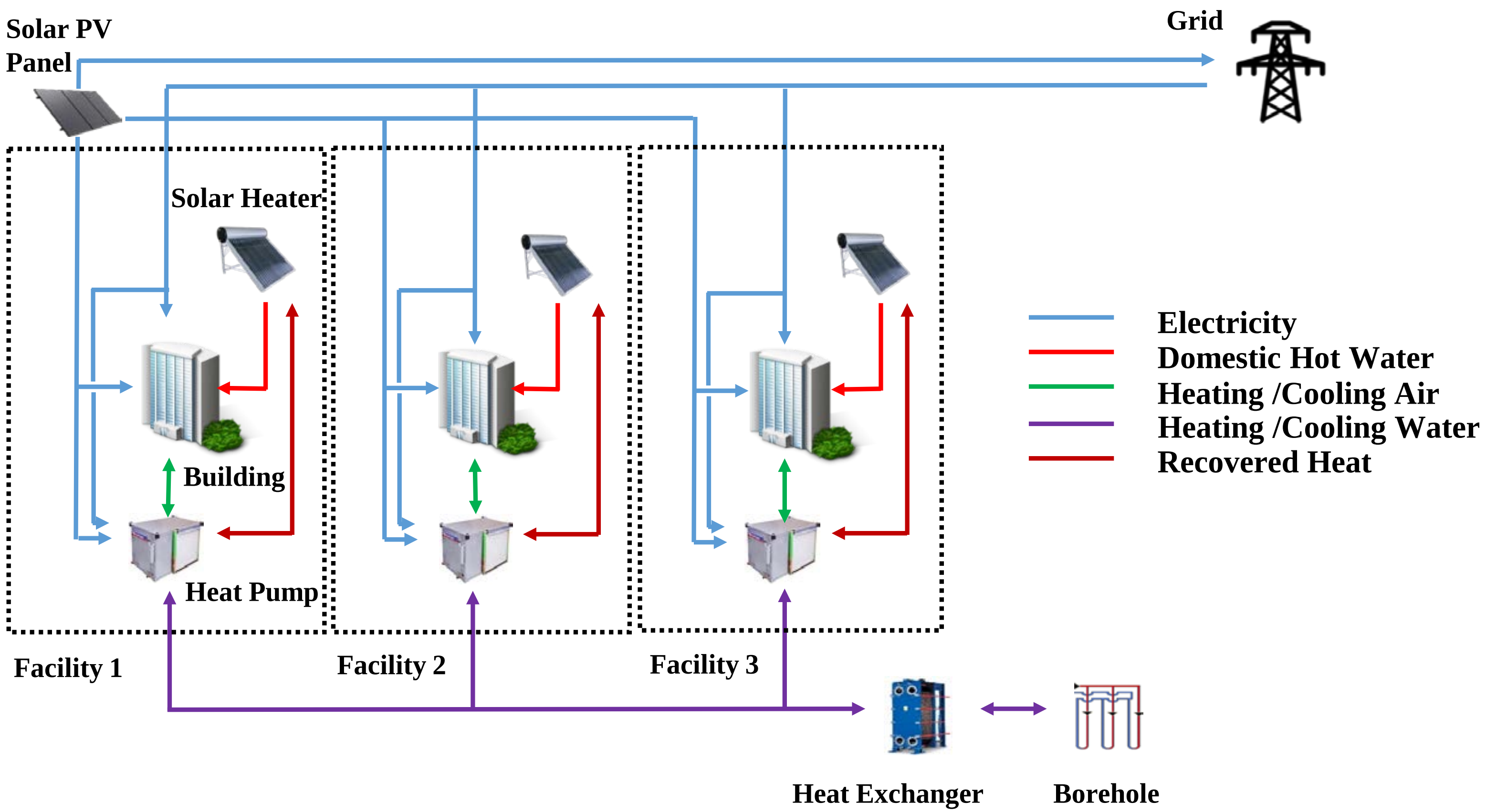
Anna Maria Island, FL

Historic Green Village

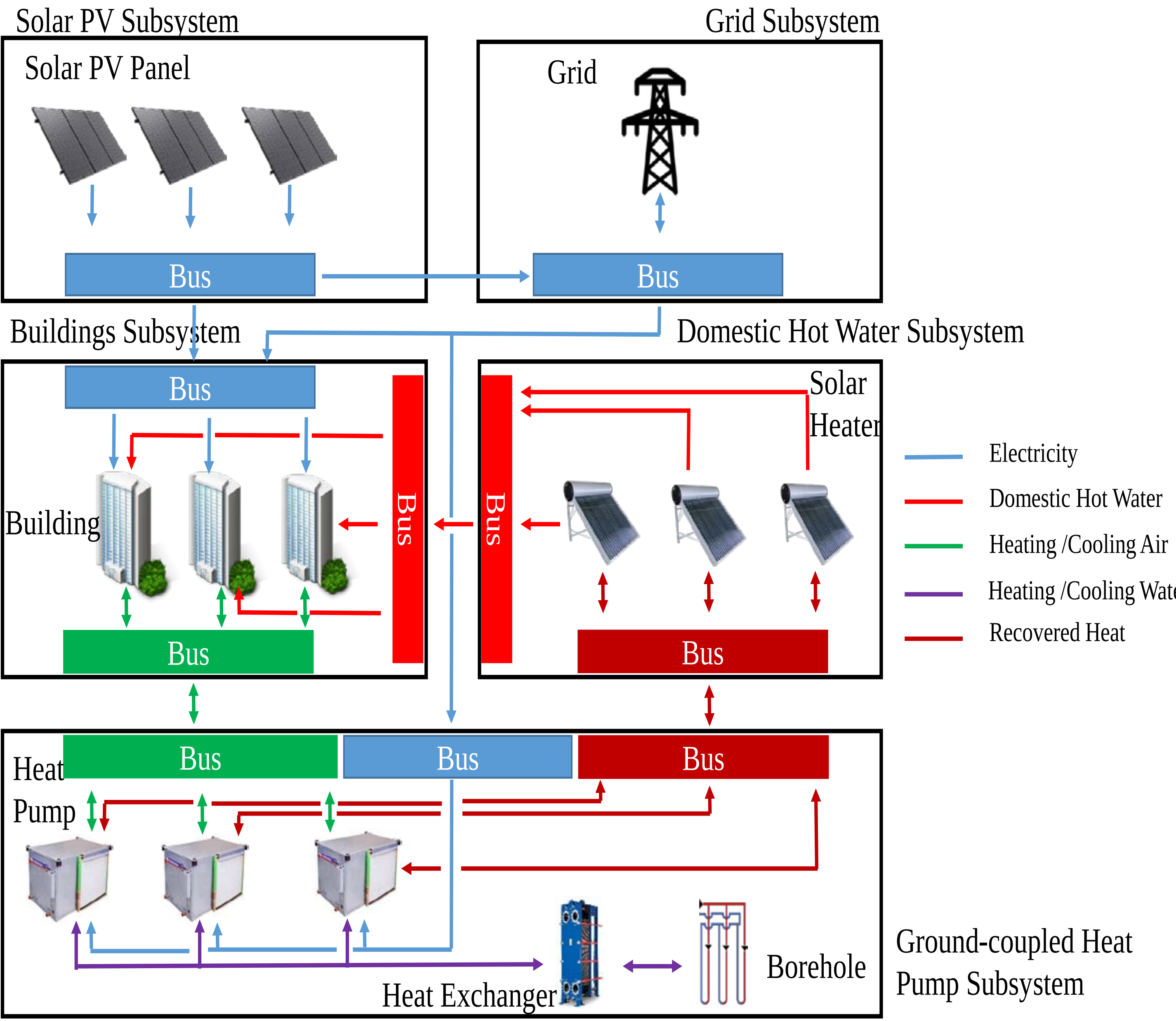
Historic Green Village, Anna Maria Island, Florida

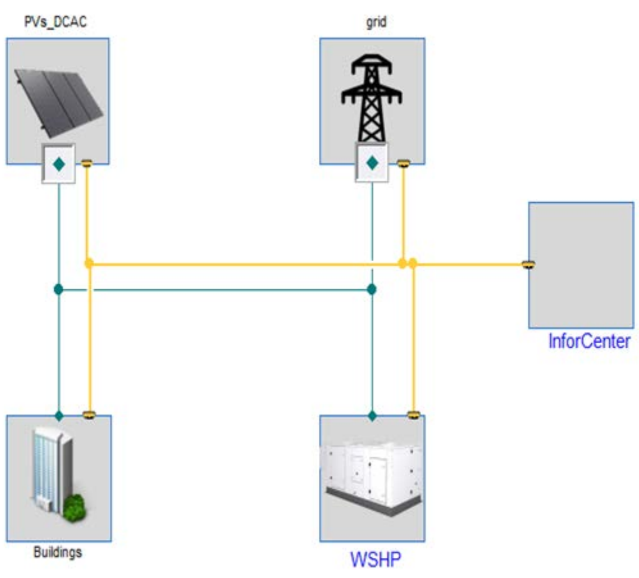
Energy subsystem

- ❑ Electric energy subsystem
- ❑ Water-source heat pump
- ❑ Solar thermal domestic hot water



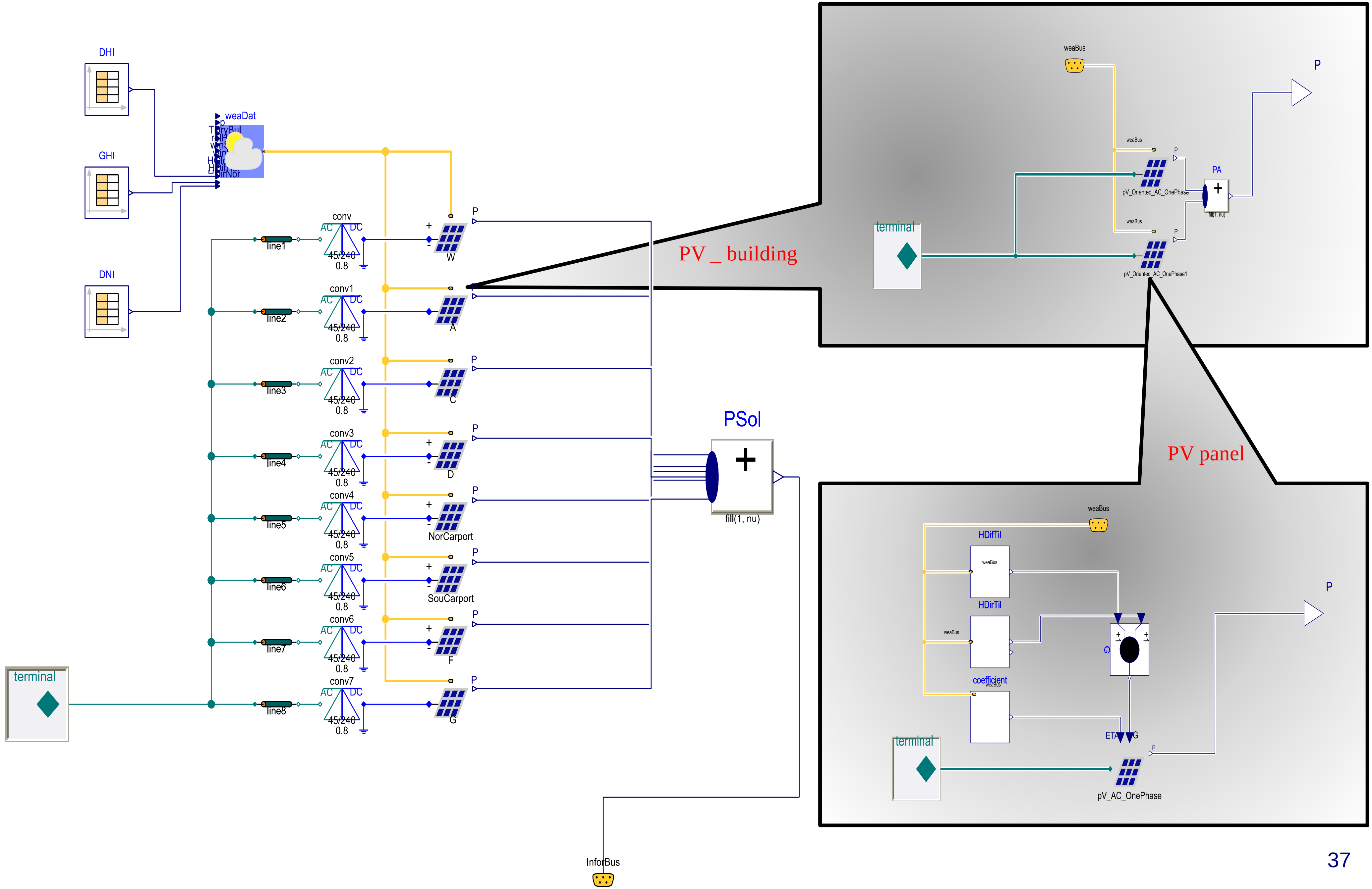
System Modeling



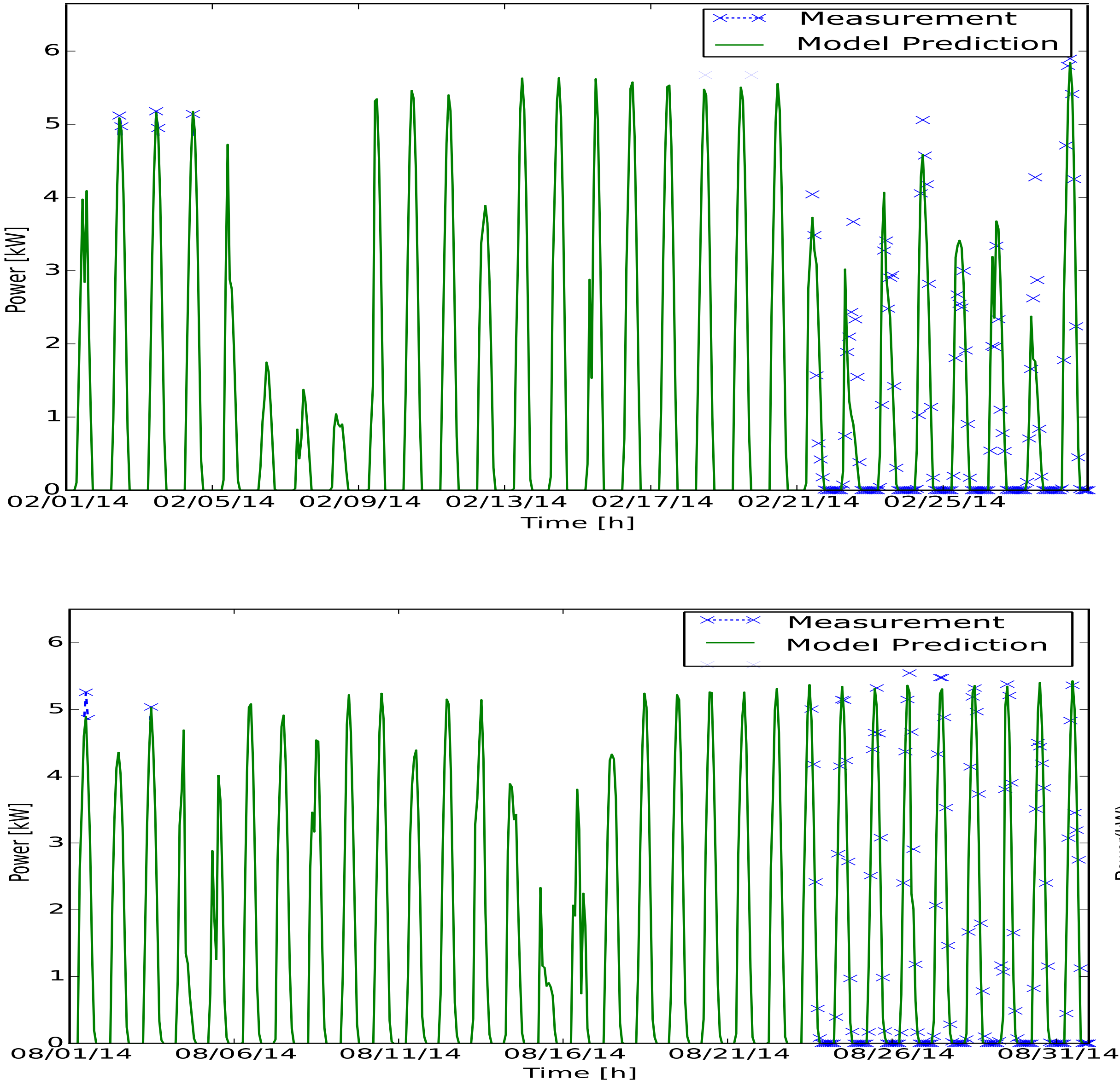


The top level model of HGV in Dymola

System Modeling: Physical Model of Solar PV Subsystem



Preliminary Results: Prediction of PV Power Generation



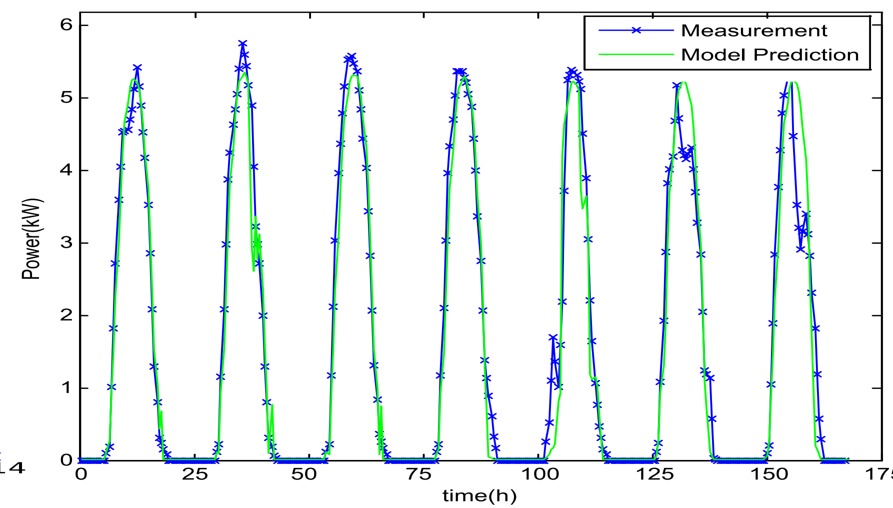
Prediction by physical model and real energy production of PVs in building Sears(D) in winter and summer of 2014: (a) in February, (b) in August.

Model	R-square
Physical	0.905(summer) 0.927(winter)
ANN	0.981

Coefficient of Determination

$$R^2 = 1 - \frac{\sum_i^{pnum}(\dot{Q}_{p,i} - \dot{Q}_{m,i})}{\sum_i^{pnum}(\overline{\dot{Q}_m} - \dot{Q}_{m,i})}$$

where $\dot{Q}_{p,i}$ and $\dot{Q}_{m,i}$ are the ith predicted and measured cooling load, $pnum$ is the prediction number, and $\overline{\dot{Q}_m}$ is the mean value of $\dot{Q}_{m,i}$.



Prediction by ANN model and real energy production of PVs in building Sears(D) from August 25, 2014 to August 31, 2014

Outline

- **Brief Introduction of Modelica**
- **Real-World Applications:**
  - Modeled-based Chilled Water Plan Optimization
  - Energy and Water Efficient Hotel
  - Net Zero Energy Community
- **Conclusion and Future Research:**
  - Energy Efficient Data Center Cooling
  - Smart and Connected Community
  - Resilient Coast City Design

Conclusion

- **Our real-world projects have demonstrated the great potential of Modelica on controls optimization and complex system design.**

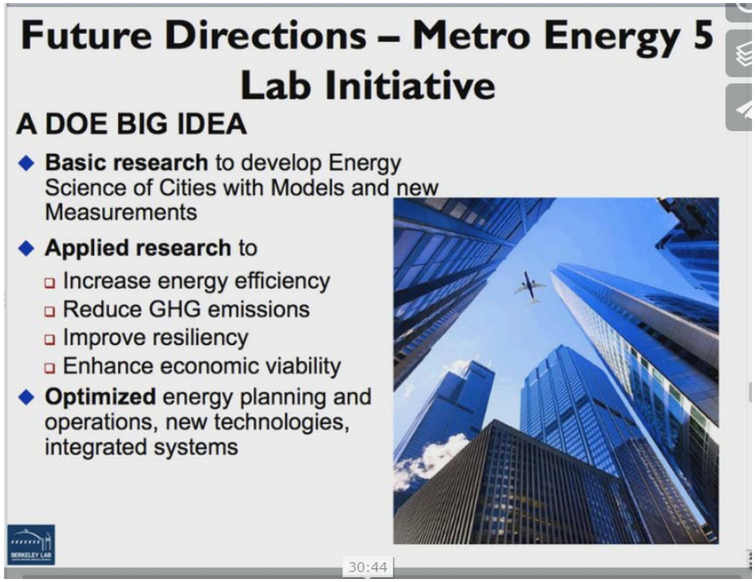
- **Combination of Modelica models with other tools can be a practical solution for real-world applications.**

Future Research

- **Extend the support of Modelica-based tools for convectional and advanced applications for buildings**

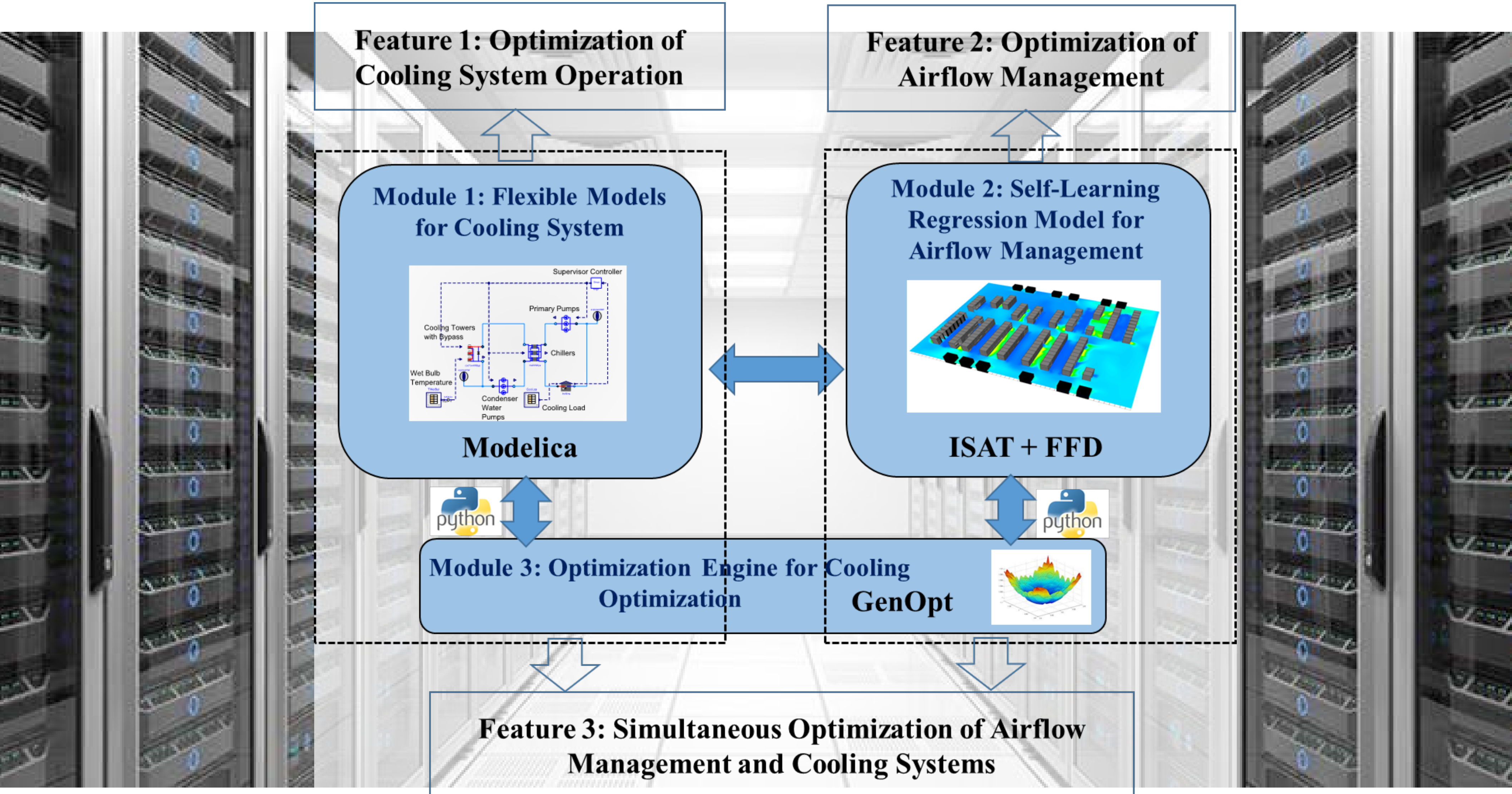
- **The Moonshot Research:**

  Smart, Sustainable, and Resilient Cities



Energy Efficient Data Center Cooling

Improving Data Center Energy Efficiency through End-to-End Cooling Modeling and Optimization (10/16-11/19), DOE, $522K, collaborate with LBNL and Schneider Electric



Smart, Sustainable and Connected Community

BIGDATA: Collaborative Research: IA: Big Data Analytics for Optimized Planning of Smart, Sustainable , and Connected Communities (9/16-8/19), National Science Foundation, $1.4M, collaborate with Virginia Tech.

A community powered by renewable energy, moved by automatic-driving electric vehicles, and connected with seamless wireless network.

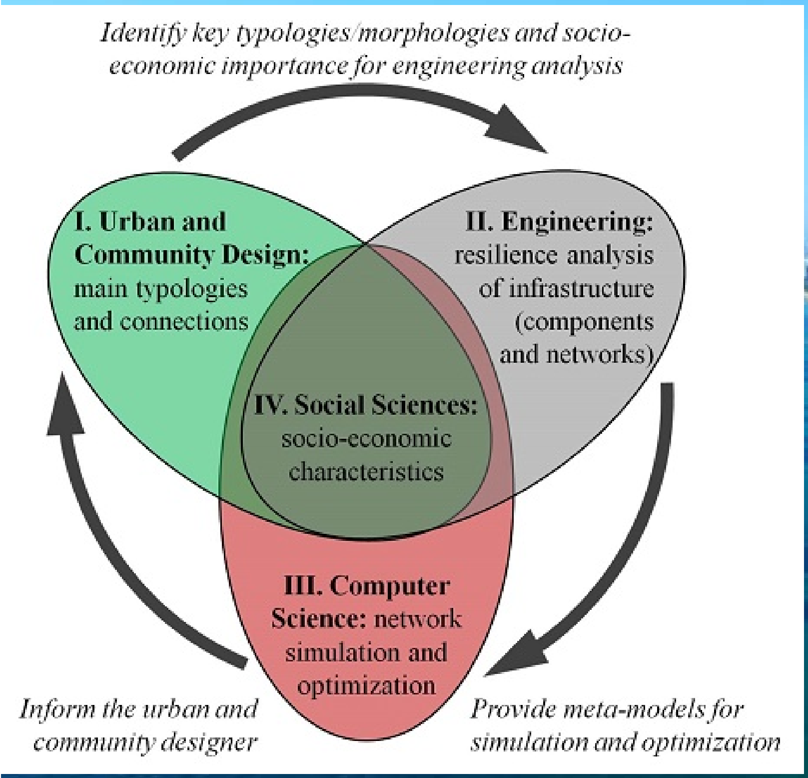
Zero-Traffic for transportation network, **Zero-Congestion** for communication network, and **Zero-Outage** for energy network

Big data analytics using real-world data, e.g. **Building Performance Database** from LBNL

Virtual Testbed: Modelica Models
Physical Testbed: Historic Green Village

Resilient Costal Cities

CRISP Type 1: Collaborative Research: A Human-Centered Computational Framework for Urban and Community Design of Resilient Coastal Cities (01/17-12/18), National Science Foundation, $500K, collaborate with Virginia Tech.



Computational framework for infrastructure network, social-economic characteristics, and urban design **based on Modelica and Functional Mockup Interface**

City of Miami Beach for case study

Smart City in Yucanta, Mexico

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