Model-Based Optimization for a Campus District Cooling System

Kathryn Hinkelman\textsuperscript{1}, Jing Wang\textsuperscript{2}, Wangda Zuo\textsuperscript{1,2}, Antoine Gautier\textsuperscript{3}, \textbf{Michael Wetter}\textsuperscript{3}, Chengliang Fan\textsuperscript{4}, Nicholas Long\textsuperscript{2}

\textsuperscript{1} Pennsylvania State University, University Park, PA, USA
\textsuperscript{2} National Renewable Energy Laboratory, Golden, CO, USA
\textsuperscript{3} Lawrence Berkeley National Laboratory, Berkeley, CA, USA
\textsuperscript{4} Guangzhou University, Guangzhou, China
Overview

• Background and motivation
• Models for district cooling systems
• Case study
• Conclusion
Background and Motivation

Why District Cooling?

• Space cooling is growing faster than any other building end use\(^1\)

• None had modeled complete district cooling systems (plant + distribution) featuring hydraulics nor waterside economizers

Objectives

• Demonstrate how Modelica can enable complete district cooling energy analysis

• Identify investment-free energy efficiency strategies for a real-world case study

• Evaluate carbon and operational cost savings due to energy retrofits

Gaps in Scientific Literature

• District cooling studies are generally limited

Case Study

- A satellite campus of University of Colorado in Boulder, CO
- Six Buildings:
  - Floor area: 93,990 m² (1,011,699 ft²)
  - Peak load: 2.4 MW
- Radial network with 1.5 km pipes
Central Plant

- Two single compressor chillers (2455 kW each)
- Three chilled water pump (30 kW each)
- Two condenser water pump (56 kW each)
- Non-integrated water side economizer
- Four cooling tower units (22 kW each)
Central Plant

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- Three chilled water pump (30 kW each)
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Modeling: District Cooling Systems

System Schematics

Top-Level Model
Central Plant

System Schematic

Cooling Tower with Bypass

Cooling Tower with Isolation Valve
Control Layer 1: Cooling Mode Control

Central Plant

State Graph

Cooling Mode Control
Control Layer 2: Chiller Staging Control

Central Plant

State Graph

Chiller Staging
Distribution Network

Connection with Two Pipes

Distribution with Two Pipes

Supply to building(s)
Return from building(s)

Heat Flow Rate
Mass Flow Rate
Pressure Drop

Supply from plant
Return from plant

Two-Pipe Connection
Lossless Pipe
connections

Return from downstream connections
Heat Port

Supply from plant
Return to plant
Supply pipe
Return pipe

Q_flow
m_flow
dp

Supplied to downstream connections

Return from building(s)
Buildings with Energy Transfer Station
Validation of Models

<table>
<thead>
<tr>
<th>Location</th>
<th>CVRMSE (%)</th>
<th>NMBE (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acceptable range: [0,30%]</td>
<td>Acceptable range: [-10,10%]</td>
</tr>
<tr>
<td></td>
<td>$Q_{CHW}$</td>
<td>$\dot{m}_{CHW}$</td>
</tr>
<tr>
<td>Plant</td>
<td>18.8</td>
<td>12.9</td>
</tr>
<tr>
<td>Chiller</td>
<td>22.2</td>
<td>15.5</td>
</tr>
<tr>
<td>Building 1</td>
<td>2.2</td>
<td>0.7</td>
</tr>
<tr>
<td>Building 2</td>
<td>2.4</td>
<td>0.1</td>
</tr>
<tr>
<td>Building 3</td>
<td>3.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Building 4</td>
<td>1.3</td>
<td>0.7</td>
</tr>
<tr>
<td>Building 5</td>
<td>1.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Building 6</td>
<td>2.2</td>
<td>0.5</td>
</tr>
</tbody>
</table>

CVRMSE (Coefficient of Variation of the Root Mean Square Error)

$$CVRMSE = \sqrt{\frac{\sum (y_i - \hat{y}_i)^2}{N - 1}} \frac{1}{\bar{y}}$$

Normalized Mean Bias Error

$$NMBE = \frac{\sum (y_i - \hat{y}_i)}{(N - 1)\bar{y}}$$

Acceptable range is based on ASHRAE Guideline 14
Model-Based System Optimization

- Condenser Water Supply Temperature
- Condenser Water Flow Rate
- Waterside Economizer
CW Supply Temperature Setpoint Optimization

**Optimization Problem**

\[
\min_{x \in [x, \bar{x}]} E_{\text{Pla},i}(T_{CW,\text{set}}(x))
\]

Total plant energy

Condenser water supply temperature setpoint

\[
E_{\text{Pla},i} = \int \left( P_{CH}(T_{CW,\text{set}}(x), s) + P_{CW P}(T_{CW,\text{set}}(x), s) + P_{CH WP}(T_{CW,\text{set}}(x), s) + P_{CT}(T_{CW,\text{set}}(x), s) \right) ds
\]

**Setpoint Methods**

- **Constant Setpoint**
  \[
  T_{CW,}\text{set} = \text{constant}
  \]

- **Fixed Approach**
  \[
  T_{CW,}\text{set} = T_{wb} + T_{app}
  \]

- **Adjusted Approach**
  \[
  T_{CW,}\text{set} = T_{wb} + (T_{app} + r_{PLR}PLR)
  \]

**Power of the:**
- (chillers)
- (CW pumps)
- (CHW pumps)
- (cooling towers)
Results of Optimizing Condenser Water Supply Temperature

\[ T_{CW,\,set}(x_1) = x_1, \]
\[ T_{CW,\,set}(x_1) = T_{wb} + x_1, \]
\[ T_{CW,\,set}(x_1, x_2) = T_{wb} + x_1 + x_2 \text{ PLR} \]

Table 4
Condenser water supply temperature optimization results.

<table>
<thead>
<tr>
<th>Case</th>
<th>Optimized $x$ Variable</th>
<th>Value</th>
<th>Energy (MWh)</th>
<th>Savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline (no optimization)</td>
<td>$x_1$</td>
<td>15.6 °C</td>
<td>551.8</td>
<td>–</td>
</tr>
<tr>
<td>Fixed $T_{CW,,set}$</td>
<td>$x_1$</td>
<td>18.7 °C</td>
<td>537.9</td>
<td>2.5</td>
</tr>
<tr>
<td>Fixed $T_{app}$</td>
<td>$x_1$</td>
<td>1.9 °C</td>
<td>527.5</td>
<td>4.4</td>
</tr>
<tr>
<td>Adjusted $T_{app}$</td>
<td>$x_1$</td>
<td>2.1 °C</td>
<td>527.5</td>
<td>4.4</td>
</tr>
</tbody>
</table>

$x_2$
Summary of Results

- **Site Energy**
- **Peak Power**
- **Cost**
- **CO₂ Emission**

**Baseline**
- No WSE
- Fixed Tcw,set
- Fixed Tapp
- Adjusted Tapp
In baseline, pumps contribute significantly to site energy use.
Summary of Results: Condenser water pump flow reduction

- 15.3% reduction in Energy
- 4.4% reduction in Peak Load
- 8.9% reduction in Cost
- 15.0% reduction in CO₂ emission
Conclusion

• Developed open source models for the Modelica Buildings for the design and operation of district cooling systems

• Case study shows significant reductions in terms of energy (15.3%), cost (8.9%) and CO₂ emission (15%).

Reference

Questions?

Wangda Zuo, Ph.D.
Email: wangda.zuo@psu.edu

Kathryn Hinkelman
Email: khinkelman@psu.edu