District Cooling Workshop

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Towards Cooperative District Cooling Society
Optimization Models for Network Design of a District Cooling System (DCS)

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Outline

- Principles of DCS
- Benefits of DCS
- Research Motivation and Scope
- Problem Description
- Methodology
- Computational Experiments
- Ongoing Research
Principles of DCS

- District cooling is the process of providing space and process cooling services to a group of customers.
- It involves two main activities:
  - Production.
  - Distribution
  - Storage (optional)
- It includes three main elements:
  - Cooling Source (chiller plant)
  - Distribution Network
  - Customers’ substations
- Capable of serving Customers of Diverse Nature:
  - Service facilities such as commercial centers, airports, hospitals, warehouses, dwellings and schools
  - Industrial facilities such as factories and production plants
Why District Cooling?

Current Status

- Worldwide, 10% of electricity is used for cooling purposes
- This percentage is even much higher in Gulf Cooperation Council (GCC) countries, where air conditioning accounts for 50% of its annual electricity consumption
- For Qatar:
  - Electricity consumption was found to be five times higher than the Middle East consumption (16.10 vs. 3.53 MWh per capita)
  - Air-conditioning currently uses close to 70% of residential power consumption during its peak in summer.
  - Features the world's highest per capita emissions with 38.17 tons of CO₂ per capita

Characteristics of DCS

- Reduces electricity consumption by **25% to 40%** comparing to conventional air conditioning system.
- Reduces energy consumption per capita.
- Supports global initiatives in reducing GHG emissions.
- Improves buildings aesthetics and design with reduced noise in buildings.
- Higher reliability
- Lower operating costs
Research Motivation and Scope

- DCS are economically sound alternatives on the long term as it requires a **relatively high capital Investment cost**.
- The economics of DCS are not only inherited and granted. Rather, they are planned and obtained.
- Further savings can be realized depending on the selected **structural and operational settings**.
  - 60% of systems investment cost is attributed to its distribution network
  - This suggests that the structural optimization of a DC network is paramount and well justified.

**Research Scope**

To develop optimization models that aids engineers in designing a minimum-cost DC systems by making optimal structural and operational decisions.
Typical Cooling Demand

Daily Demand Pattern

Cooling Load (Tons)

Cooling Load (KW)

Time of the Day

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200 210 220 230 240 250

0 50 100 150 200 250 300 350 400 450 500 550 600 650

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

0 50 100 150 200 250 300 350 400 450 500 550 600 650
**Problem Description**

- **Central Chiller Plant**
  - Chiller
  - Storage Tank

**District served by a central chiller plant**

- **Chiller Plant**
  - Plant capacity
  - Quantities to be produced during every period $t \in T$

- **Storage Tank**
  - Tank capacity
  - Quantities to be stored during every period $t \in T$

- **Distribution Network**
  - Selection of connection routes (network layout)
  - Selection of pipe size (network size)
Thermal Aspects

The diagram illustrates the temperature gradient along the distance from the central plant to multiple customers. The temperature gradient is shown as a linear decrease from the central plant to each customer, with specific points marked as $t_{j=1}$, $t_{j=2}$, $t_{j=3}$, $t_{j=4}$, and $t_{j=5}$. The maximum temperature difference is indicated as $\Delta T_{max}$. The supply and return pipe gradients are also highlighted, with the supply pipe gradient showing a decrease from the central plant to the customer, and the return pipe gradient showing the temperature rise back to the central plant.
Hydraulics Aspects

- Supply Pipe Gradient
- Return Pipe Gradient
- Pressure Gradient (Bar)
- Distance (km)
- Central Plant
- Customer1
- Customer2
- Customer3
- Customer4
- Customer5

\[ P_{\text{max}} \]
\[ P_{j=1} \]
\[ P_{j=2} \]
\[ P_{j=3} \]
\[ P_{j=4} \]
\[ P_{j=5} = P_{\text{min}} \]
\[ \Delta P_{\text{max}} \]
\[ \delta P_{\text{min}} \]
\[ \bar{P} \]
Two Mixed Integer Programming models for the optimal design of DCS are developed to aid in finding:

- The optimal **chiller plant size**.
- The optimal **storage tank size**.
- The optimal **piping network size and layout**.
- The optimal **quantities produced** and **stored** during each period of time.

While considering **structural** and **technical** constraints (including temperature and pressure related ones).
Plant Design and Operations (PDO) Model

Minimize

\[ \sum_{k \in K} FC_{plant}^k y_k + \sum_{h \in H} FC_{storage}^h g_h + \sum_{t \in T} VC_{pro}^t F_t + \sum_{t \in T} VC_{sto}^t I_t \]

Subject to:

\[ \sum_{k=1}^{K} y_k = 1, \]

\[ \sum_{h=1}^{H} g_h \leq 1 \]
Cont. PDO Model

\[ F_t \leq \sum_{k \in K} Q_k y_k \quad \forall t \in T \]

\[ I_t \leq \sum_{h \in H} D_h g_h \quad \forall t \in T \]

\[ I_{t-1} + \tau F_t = I_t + \tau \sum_{j=1}^{n} d_{jt} \quad \forall t \in T \]

\[ I_o = I_T \]

\[ F_t, I_t \geq 0 \quad \forall t \in T \]

\[ y_k, g_h \in \{0,1\} \quad \forall k \in K, \forall h \in H \]
Network Design (ND) Model

Minimize

\[ \sum_{(i,j) \in A} \sum_{m \in M} c_{ij}^m x_{ij}^m \]

Subject to:

\[ \sum_{i \in V_j} z_{ij} = 1 \quad \forall j \in C \]

\[ \sum_{i \in V_j} z_{ij} \leq 1 \quad \forall j \in S \]
Cont. ND Model

\[
\sum_{m \in M} x_{ij}^m = z_{ij} \quad \forall (i, j) \in A
\]

\[
\sum_{i \in V_j} \sum_{m \in M} f_{ij}^{tm} - \sum_{k \in V^+_j} \sum_{m \in M} f_{ij}^{tm} = d_{jt} \quad \forall j \in C, \quad \forall t \in T
\]

\[
\sum_{i \in V_j} \sum_{m \in M} f_{ij}^{tm} = \sum_{k \in A^+_j} \sum_{m \in M} f_{ij}^{tm} \quad \forall j \in S, \quad t \in T
\]

\[
\varphi_{min} x_{ij}^m \leq f_{ij}^{tm} \leq \varphi_{max} x_{ij}^m \quad \forall (i, j) \in A, \quad \forall m \in M, \quad t \in T
\]
Cont. ND Model

Temperature-related Constraints

\[ t_j z_{ij} = t_i z_{ij} + \sum_{m \in M} \Delta T_{ij}^m x_{ij}^m \]
\[ t_{min} \leq t_j \leq t_{max} \quad \forall (i, j) \in A \]

\[ t_{min} \sum_{i \in V_j} z_{ij} \leq t_j \leq t_{max} \sum_{i \in V_j} z_{ij} \quad \forall j \in C \]

\[ t_r = t_{min} \quad \forall j \in S \]
Cont. ND Model

Pressure-related Constraints

\[ P_{ij}z_{ij} = P_{i}z_{ij} - \sum_{m\in M} \Delta p_{ij}^m x_{ij} \quad \forall (i, j) \in A \]

\[ P_{\text{min}} \leq P_{j} \leq P_{\text{max}} \quad \forall j \in C \]

\[ P_{\text{min}} \sum_{i \in A_j} z_{ij} \leq P_{j} \leq P_{\text{max}} \sum_{i \in A_j} z_{ij} \quad \forall j \in S \]

\[ P_r = P_{\text{max}} \]
Cont. ND Model

\[ x_{ij}^m, z_{ij} \in \{0,1\} \]

\[ f_{ij}^{tm} \geq 0 \]

\[ f_{ij}^m \geq 0 \]

\[ t_j, P_j \geq 0 \]

\[ \forall (i, j) \in A \]

\[ \forall m \in M \]

\[ \forall (i, j) \in A \]

\[ \forall (i, j) \in A \]

\[ t \in T \]

\[ m \in M \]

\[ \forall j \in C \cup S \]
Both Models were tested and implemented using a commercial general-purpose solver (CPLEX)

- Various networks that contained up to 60 nodes were assumed and solved.
- On average, 3.3 hours of CPU time is required to solve the largest assumed network.
- The CPU time to reach optimality is very sensitive to the number of design periods.
Ongoing Research

- Multiple chiller plants system (One large plant versus multiple plants: cost, flexibility, reliability)

- This involves optimizing decisions related to:
  - Chiller Plant
    - Number of plants
    - Location of each plant
    - Plants’ Capacity
    - Quantities to be produced every period of time (e.g. hour)
  - Thermal Energy Storage (TES)
    - Number of tanks
    - Location of each tank
    - Plants’ Capacity
    - Quantities to be stored every period of time (e.g. hour)
  - Primary Distribution Network
    - Piping Layout
    - Piping Size
  - Energy Transfer Station (ETS)
    - Integration with distribution network by selecting the appropriate heat exchangers (based on pressure limits)
Reduce CO2 footprint by using a clever mix of conventional electricity/gas driven chillers and absorption chillers.

Absorption chillers may either use waste heat (e.g. power/desalination plant) or solar energy.