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Towards Cooperative District Cooling Society

جامعة قطر
QATAR UNIVERSITY

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, dw ellings 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 **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 CO_2 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

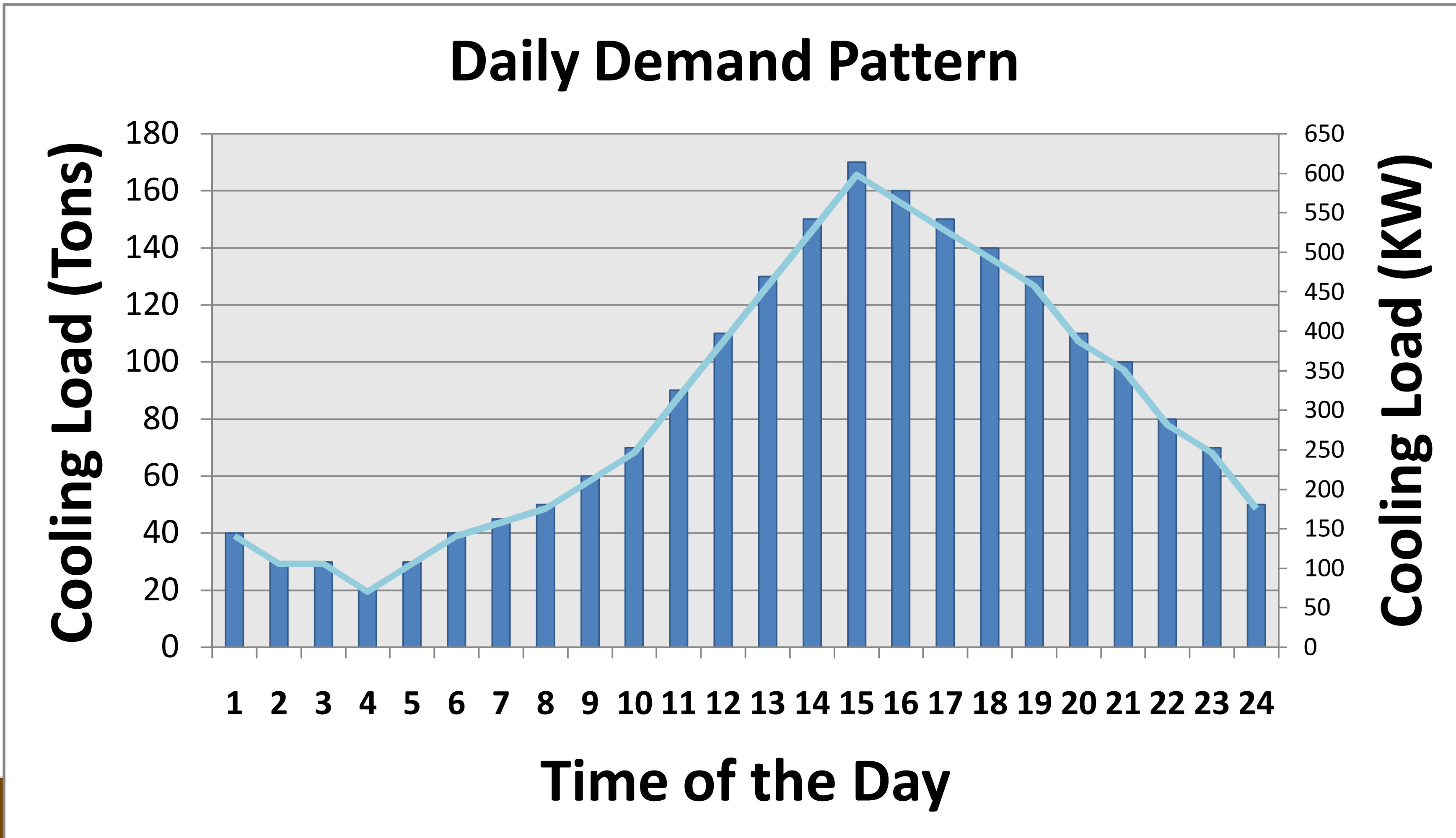
Research Motivation and Scope

- 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.

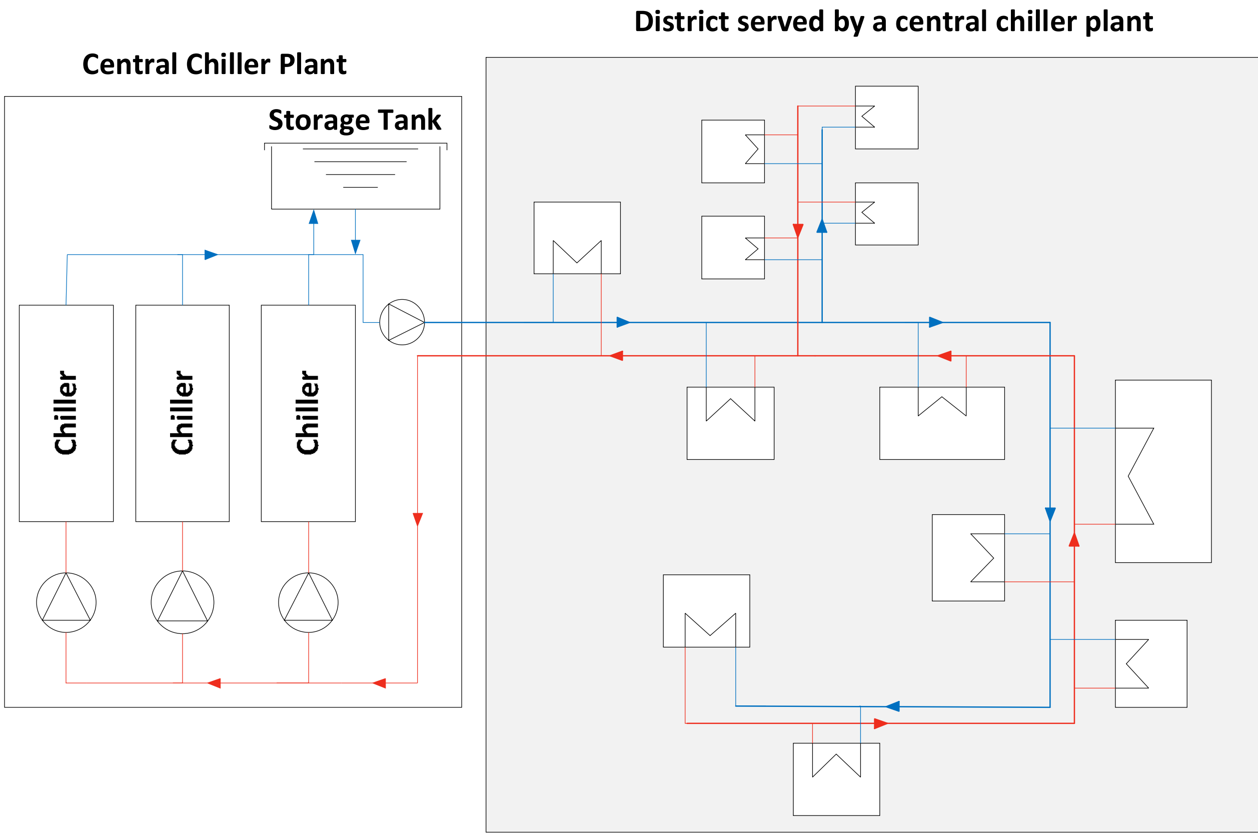
Research Scope

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

Typical Cooling Demand



Problem Description



Chiller Plant

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

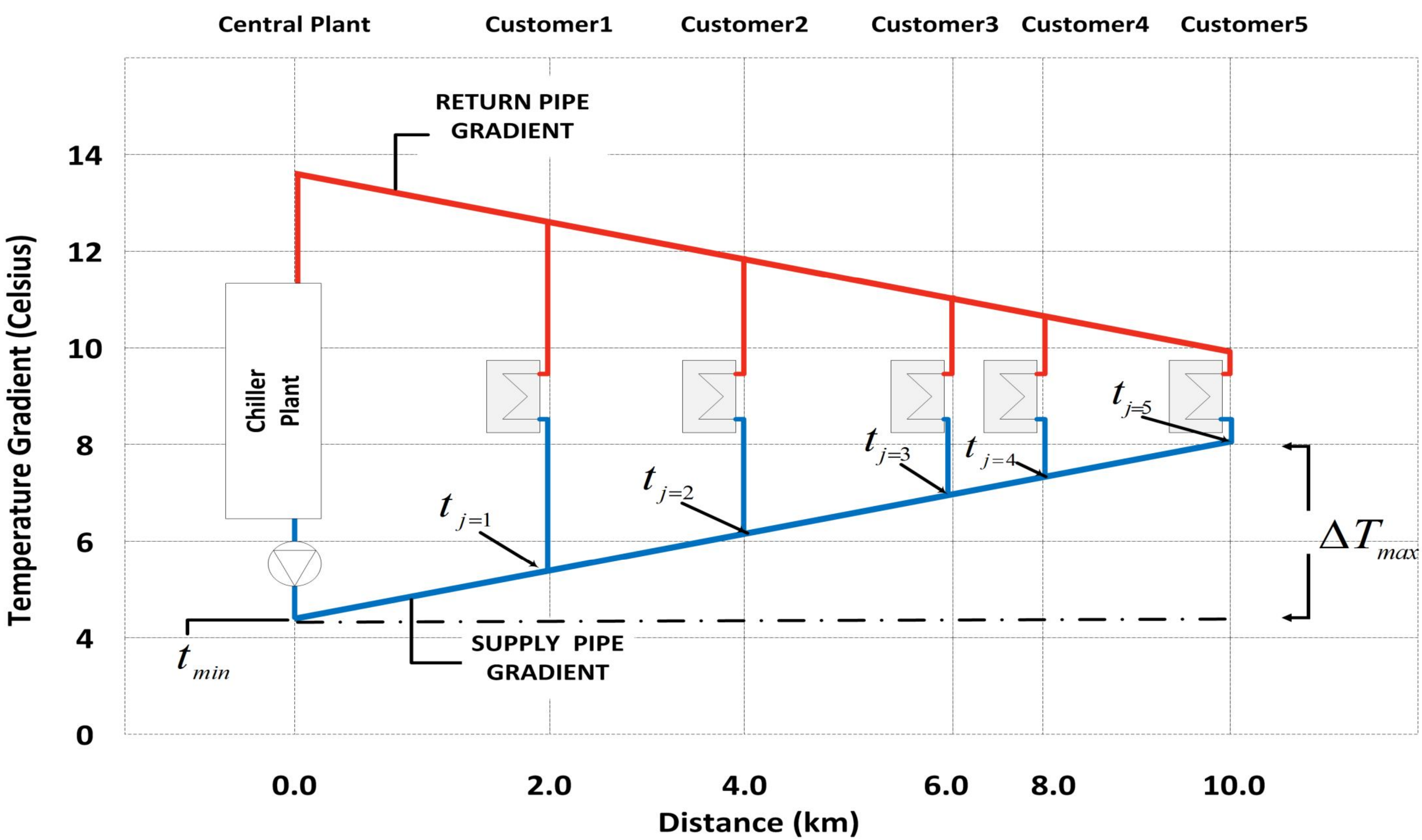
Storage Tank

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

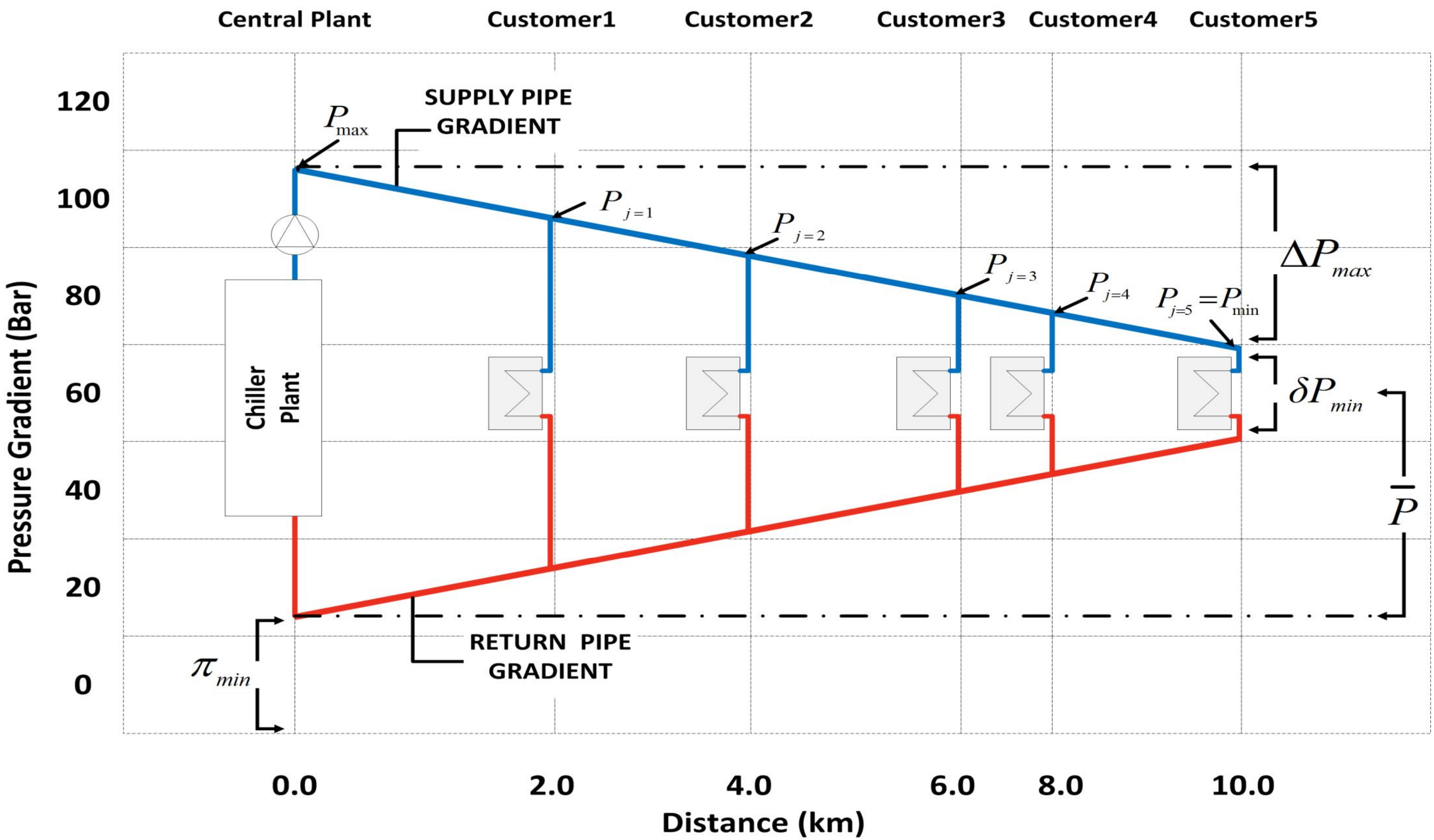
Distribution Network

- Selection of connection routes (network layout)
- Selection of pipe size (network size)

Thermal Aspects



Hydraulics Aspects



Methodology

- 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

$$\sum_{k \in K} FC_k^{plant} y_k + \sum_{h \in H} FC_h^{storage} g_h + \sum_{t \in T} VC_t^{pro} F_t + \sum_{t \in T} VC_t^{sto} I_t$$

- Subject to:

$$\sum_{k=1}^{K} y_k = 1,$$

$$\sum_{h=1}^{H} g_h \le 1$$

Cont. PDO Model

$$F_t \leq \sum_{k \in K} Q_k y_k \qquad \forall t \in T$$

$$I_t \leq \sum_{h \in H} D_h g_h \qquad \forall t \in T$$

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

$$I_o = I_T$$

$$F_t, I_t \geq 0 \qquad \forall t \in T$$

$$y_k, g_h \in \{0,1\} \qquad \forall k \in K, \quad \forall h \in H$$

Network Design (ND) Model

- Minimize

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

Subject to:

$$\sum_{i\in V_j^-} z_{ij} = 1 \qquad \forall\, j \in C$$

$$\sum_{i\in V_j^-} z_{ij} \leq 1 \qquad \forall\, j \in S$$

Cont. ND Model

$$\sum_{m \in M} x_{ij}^{m} = z_{ij} \qquad \forall (i,j) \in A$$

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

$$\sum_{i \in V_j^-} \sum_{m \in M} f_{ij}^{tm} = \sum_{k \in A_j^+} \sum_{m \in M} f_{ij}^{tm} \qquad \forall\, j \in S \quad t \in T$$

$$\varphi_{min}^{m} x_{ij}^{m} \leq f_{ij}^{tm} \leq \varphi_{max}^{m} x_{ij}^{m} \qquad \forall (i,j) \in A \quad \forall\, m \in M \quad t \in T$$

Cont. ND Model

Temperature-related Constraints

$$t_j z_{ij} = t_i z_{ij} + \sum_{m \in M} \Delta T_{ij}^m x_{ij}^m \qquad \forall (i,j) \in A$$

$$t_{min} \leq t_j \leq t_{max} \qquad \forall\, j \in C$$

$$t_{min} \sum_{i \in V_j^-} z_{ij} \leq t_j \leq t_{max} \sum_{i \in V_j^-} z_{ij} \qquad \forall\, j \in S$$

$$t_r = t_{min}$$

Cont. ND Model

Pressure-related Constraints

$$P_j z_{ij} = P_i z_{ij} - \sum_{m \in M} \Delta p_{ij}^m x_{ij}^m \qquad \forall (i,j) \in A$$

$$P_{min} \leq P_j \leq P_{max} \qquad \forall\, j \in C$$

$$P_{min} \sum_{i \in A_j^-} z_{ij} \leq P_j \leq P_{max} \sum_{i \in A_j^-} z_{ij} \qquad \forall\, j \in S$$

$$P_r = P_{max}$$

Cont. ND Model

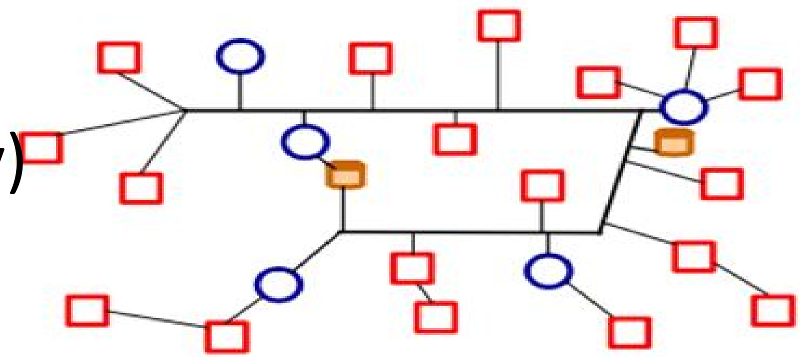
$x_{ij}^{m}\ , z_{ij} \in \{0,1\}$	$\forall (i,j) \in A$ $\forall\ m \in M$
$f_{ij}^{tm} \geq 0$	$\forall (i,j) \in A$
$f_{ij}^{m}\ \geq 0$	$\forall (i,j) \in A$ $t \in T$ $m \in M$
$t_j\ , P_j \geq 0$	$\forall\ j \in C \cup S$

Computational Experiments

- 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:

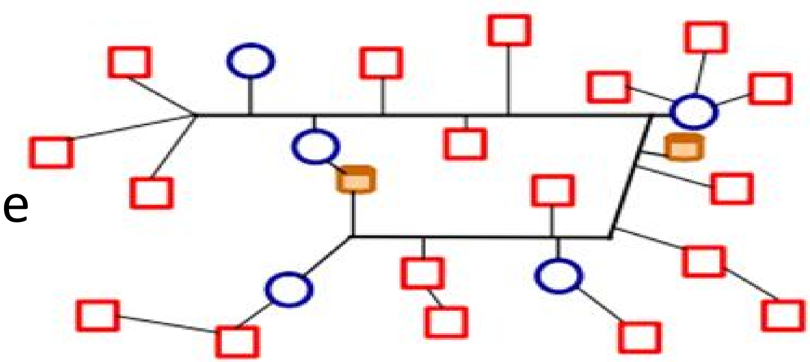


Chiller Plant	Thermal Energy Storage (TES)	Primary Distribution Network	Energy Transfer Station (ETS)
Number of plants	Number of tanks	Piping Layout	Integration with distribution network by selecting the appropriate heat exchangers (based on pressure limits)
Location of each plant	Location of each tank	Piping Size	
Plants' Capacity	Plants' Capacity		
Quantities to be produced every period of time (e.g. hour)	Quantities to be stored every period of time (e.g. hour)		

Consumer buildings
Central chiller plant
Storage

Ongoing Research

- Reduce CO_2 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.



Chiller Plant

- Optimal mix of conventional/absorption 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)