MITSUBISHI ELECTRIC
RESEARCH LABORATORIES

Optimization of circuitry arrangements for heat exchangers

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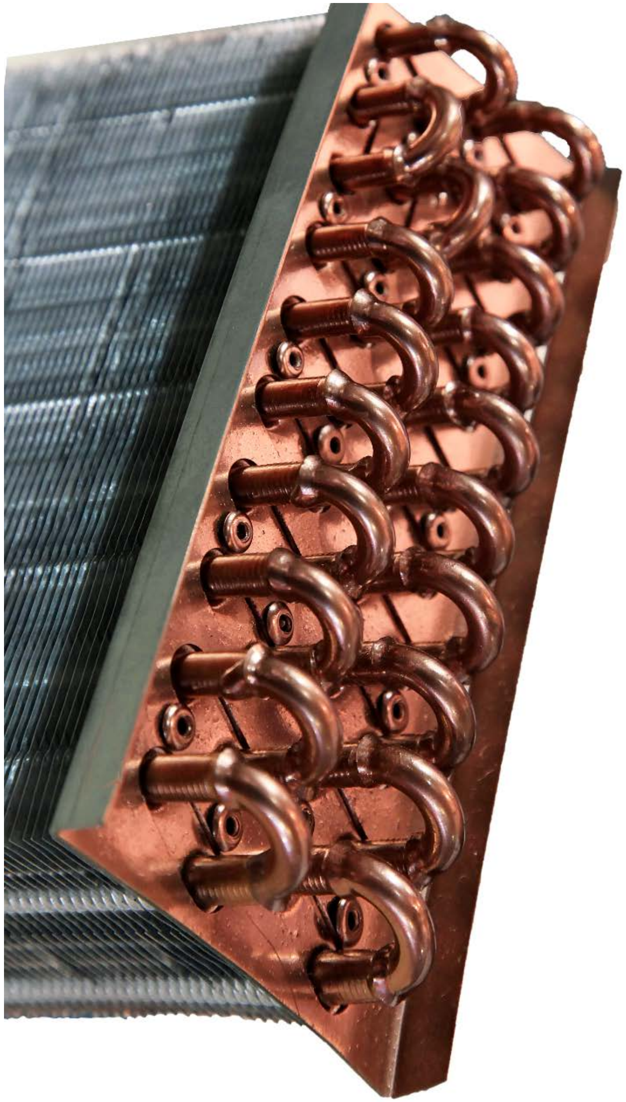
MOTIVATION



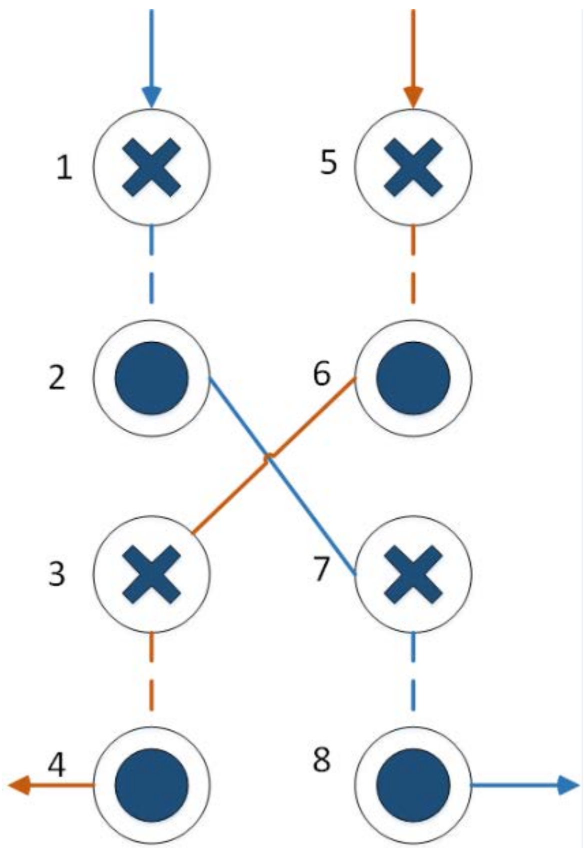
- **Optimize refrigerant circuitry design of heat exchangers (HEX)**
- **Use only realistic manufacturing constraints**
- **Apply derivative-free optimization (DF0) solvers**
- **Validate results using constraint programming**

PROBLEM STATEMENT

- **Develop a systematic optimization method to determine an optimal circuitry configuration**
- **Incorporate only realistic manufacturing constraints without requiring extensive domain knowledge**
- **Use detailed first-principles model to assess the performance of different refrigerant circuitry designs**
  - **CoilDesigner**

PROBLEM REPRESENTATION

- **Depict circuitry configuration as a graph**



$$\begin{bmatrix} 0&1&0&0&0&0&0&0\\ 1&0&0&0&0&0&1&0\\ 0&0&0&1&0&1&0&0\\ 0&0&1&0&0&0&0&0\\ 0&0&0&0&0&1&0&0\\ 0&0&1&0&1&0&0&0\\ 0&1&0&0&0&0&0&1\\ 0&0&0&0&0&0&1&0 \end{bmatrix}$$

$$\begin{bmatrix} 0 & x_1 & x_2 & \cdots & \cdots & x_{t-1} \\ 0 & 0 & x_t & x_{t+1} & \cdots & x_{2t-3} \\ \vdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & 0 & \cdots & \cdots & x_{(t^2-t)/2} \\ 0 & 0 & 0 & \cdots & \cdots & 0 \end{bmatrix}$$

Treat the graph as undirected and limit the variables to *$(n^2 - n)/2$*

OPTIMIZATION MODEL

- **Two objective functions are considered**
  - Maximize heat capacity

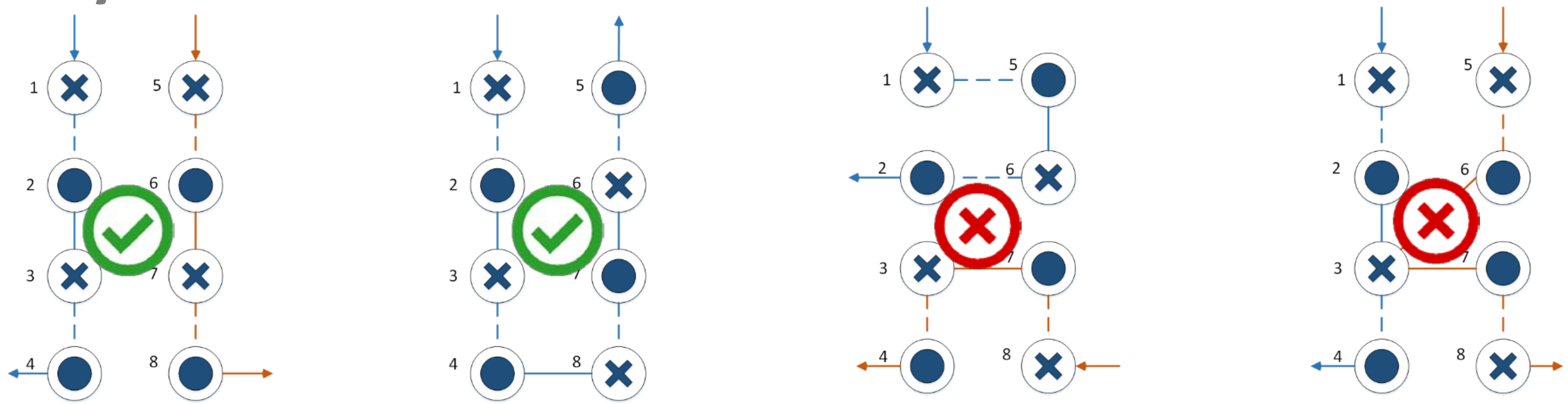
$$
\begin{aligned}
\max\ & Q(x) \\
\text{s.t.}\ & \text{constraints on the farther end} \\
& \text{constraints on the front end} \\
& x_i \in \{0,1\}, i = 1,2,...,n
\end{aligned}
$$

  - Maximize the ratio of heat capacity to pressure difference across the heat exchanger

$$
\begin{aligned}
\max\ & \frac{Q(x)}{\Delta P(x)} \\
\text{s.t.}\ & Q(x) \geq Q_{lim} \\
& \text{constraints on the farther end} \\
& \text{constraints on the front end} \\
& x_i \in \{0,1\}, i = 1,2,...,n
\end{aligned}
$$

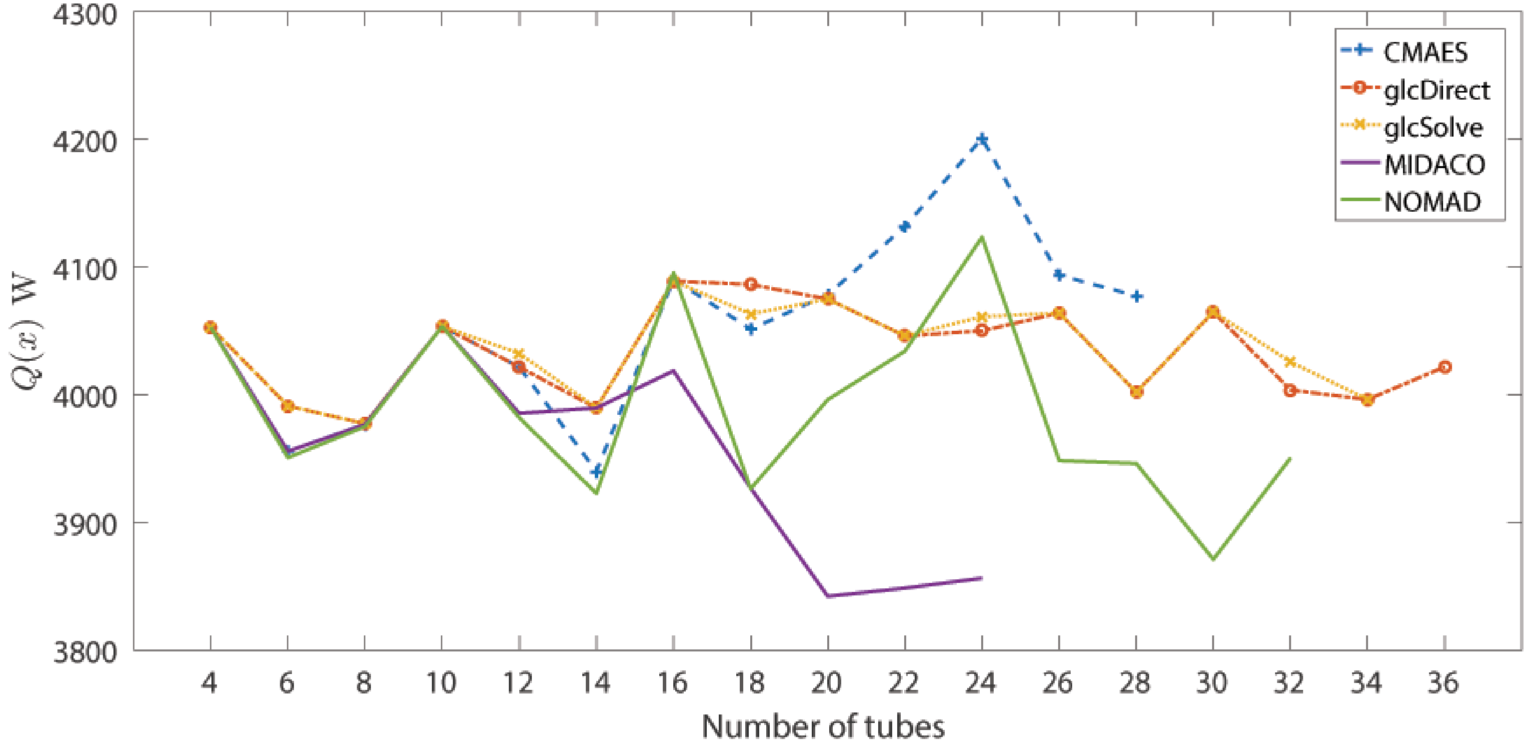
CONSTRAINTS

- **Connections on the farther end**
  - Plugged tubes are not allowed
  - The connections on the farther end cannot be across rows unless they are at the edge of the coil
- **Connections on the front end**
  - Merges and splits are not allowed
  - Cycles are not allowed



COMPUTATIONAL RESULTS

- **Five mixed-integer constrained DFO solvers applied to solve instances with 4 – 36 tubes**



VALIDATION USING CONSTRAINT PROGRAMMING

- **We formulated the circuitry optimization problem as a constraint satisfaction problem using Choco solver**

# of tubes	*Q(x) W*				*Q(x)/ΔP(x) (W/kPa)*			
	min	average	max	best DFO	min	average	max	best DFO
4	3,619	3,807	4,053	4,053	407	410	413	413
6	3,234	3,700	3,991	3,991	254	268	280	280
8	2,963	3,675	3,977	3,977	190	560	1,446	1,443
10	2,643	3,649	4,053	4,053	147	775	8,906	8,905
12	2,528	3,716	4,034	4,032	120	575	8,229	8,216

NOVELTY/SIGNIFICANCE

- **Realistic formulation for circuitry design**
- **Novel binary constrained optimization model with a black-box objective function**
- **Five mixed-integer DFO solvers were compared**
- **Near-optimal solutions are found with a small number of simulations**
- **Constraint programming was used to verify the results for small coils**

IMPACT ON PRACTICAL APPLICATIONS

- **The proposed approach improves the performance of heat exchangers**
  - No guarantee that a manual configuration will be optimal; a systematic optimization method is needed
  - Freeing up engineering time
- **Coils with up to 36 tubes were optimized**
- **Memory-intensive for larger coils**
- **Add splits/merges to the formulation**