

APPLICATION OF GENETIC ALGORITHM WITH LOCAL SEARCH IN OPTIMAL PIPING NETWORK DESIGN OF A DISTRICT COOLING SYSTEM

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ABSTRACT

District cooling system (DCS) is a mass-scale production of chilled water generated at a central and remote chiller plant. Through an underground piping network, the chilled water is delivered to serve a group of consumer buildings in a district area. DCS can offer both economical and environmental benefits. Because of the substantial capital investment and running energy involved, an optimal design of the distribution piping network is one of the crucial factors for successful implementation of the district cooling scheme. However, it is impractical to evaluate the huge number of different combinations of piping configuration by exhaustive approach. In the present study, genetic algorithm (GA) was applied to find the optimal or near-optimal configuration of the piping network in a hypothetical district area. In order to improve the solution quality and computational efficiency of the optimization process, a new local search technique was developed and incorporated into GA. The results are encouraging that the local search technique developed can search better solution in the vicinity of a current near-optimal solution. The details of the present study and the future work to be followed are presented in this paper.

KEYWORDS

District cooling system; Piping network; Genetic algorithm; Local search

INTRODUCTION

District cooling system (DCS) is a massive and collective cooling energy production scheme. Chilled water is produced in a remote central chiller plant, and is delivered to serve a group of buildings and/or facilities through a closed-loop piping network. The overall system efficiency is higher than the individual chiller plants installed at single buildings. This is achieved, firstly, through the mass-scale production in which larger chillers with higher efficiency are in use, and secondly, through the thermal load diversion in which the installed cooling capacity at the central chiller plant can be smaller than the total capacity to be installed at the customer buildings. Moreover, DCS customers can utilize their building space more effectively since the installation of their own cooling facilities is no longer required. From the environmental point of view, the pollutant (like CFC) emissions and wastes from a remote district cooling plant site are easier to be taken care of than those released from small and scattered cooling plants all over the district. The above economical and environmental benefits are best experienced in a modern tropical or subtropical city where the cooling load density is high – typically in association with tall buildings.

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In district cooling plant, chilled water is distributed to the consumer buildings through a large underground piping network with length in the order of kilometers. The general forms of chilled water distribution piping network are usually in two forms, namely radial and tree shape. In radial distribution, a pair of supply and return water pipes extend directly from a DCS plant to each target building through the shortest route. This is suitable for several target buildings scattered loosely in different directions around the DCS plant. In tree shape distribution, main supply and return pipes are extended from the source to target buildings located on similar directions and then branches are extended to distribute chilled water to the target buildings. This is suitable for a number of target buildings concentrated in a few directions at different distances. In most cases, radial and tree shape distributions are combined together for a DCS plant surrounded by a number of target buildings.

For designing the suitable piping network configuration for a DCS plant, a number of factors have to be considered such as location of district cooling plant and target buildings, the distance and obstructions in between, dimension and length of pipe work, pumping energy of chilled water distribution system, etc. In the present study, minimum infrastructure (piping) cost and distribution pumping cost are set as the objective in order to design an optimum configuration for the piping network of a DCS. Exhaustive searching for an optimum configuration which requires extremely long time and expensive computing cost is impractical. Therefore, one of the natural optimization methods, genetic algorithm (GA) is applied in the present work to search the optimal piping network configuration

METHODOLOGY

Building thermal loads

In the present study, the objective is to search an optimal piping configuration of a DCS with minimum sum of pipe work and pumping costs. In order to determine the pumping cost, the hourly chilled water demand of each DCS consumer building was first developed. The buildings in the entire district were categorized based on the similarity in their nature of operation and energy consumption profiles to establish a database of the space cooling loads per unit floor area of the different types of buildings. The generic model building of each building category, with regard to the construction materials, physical size and facilities, was then developed. The internal load densities and the daily operating schedules for the three day types (weekday, weekend and holiday) were assigned, making reference to the local building energy code published by the Hong Kong Special Administrative Region Government (HKSAR 2003). Using a dynamic building simulation software EnergyPlus (DOE 2005) and the hourly weather data of a typical meteorological year (TMY) developed for Hong Kong (Chan et al. 2005), the thermal load analysis of each generic model building was executed. Through the process, normalized cooling load profiles of each model building in W/m^2 were determined. The total cooling load was estimated by the normalized cooling load of each model building category multiplied by the corresponding total floor area that requires air-conditioning. Finally, the data set of the year-round hourly cooling load as well as hourly chilled water demand of all the building categories was developed. More detailed description of this approach for the cooling demand estimation can be found in Chow et al. (2004).

Genetic algorithm

Optimization of piping network is one type of the combinatorial problems which are impractical to be solved by exhaustive searching approach. In this aspect, GA offers its advantage with its probabilistic search heuristics to carry out searching for optimal/near-optimal solution over the entire search domain. In the following paragraphs, the optimization process of the piping configuration in a DCS using GA including encoding, solving algorithm as well as local search technique are described in details.

One of the most crucial factors for a successful implementation of GA is the representation of an underlying problem by a suitable scheme. In the present study, integer-string representation is used to encode the piping network. This encoding method had been used successfully to represent water distribution system (Savic and Walters 1995) and knapsack problem (Thiel and Voss 1994) by different researchers. With this integer-string representation, every possible link was assigned with an integer. The number of integers should be equal to $n - 1$, where n is the number of nodes in the piping network. This kind of encoding is uniformly redundant, i.e. each phenotype is represented by the same number of genotypes. Infeasible candidate (network) may be generated which will be checked and repaired. An example of a piping configuration of problem size 9 with integer-string representation is illustrated in Figure 1 and Table 1. In Figure 1, node 1 is a DCS central plant which supplies chilled water to the consumer buildings (nodes 2 – 9) through a piping network. This configuration is encoded by an integer-string {1, 5, 8, 9, 23, 27, 34, 35} as listed in shaded cells of Table 1.

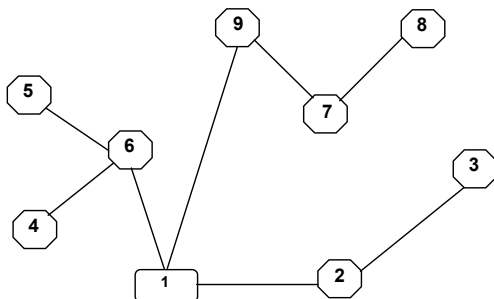


Figure 1. An example network with integer-string {1, 5, 8, 9, 23, 27, 34, 35}

Table 1 Integer-string encoding

| Integer label | Link | Integer label | Link | Integer label | Link |
|---------------|------|---------------|------|---------------|------|
| 1 | 1-2 | 13 | 2-7 | 25 | 4-8 |
| 2 | 1-3 | 14 | 2-8 | 26 | 4-9 |
| 3 | 1-4 | 15 | 2-9 | 27 | 5-6 |
| 4 | 1-5 | 16 | 3-4 | 28 | 5-7 |
| 5 | 1-6 | 17 | 3-5 | 29 | 5-8 |
| 6 | 1-7 | 18 | 3-6 | 30 | 5-9 |
| 7 | 1-8 | 19 | 3-7 | 31 | 6-7 |
| 8 | 1-9 | 20 | 3-8 | 32 | 6-8 |
| 9 | 2-3 | 21 | 3-9 | 33 | 6-9 |
| 10 | 2-4 | 22 | 4-5 | 34 | 7-8 |
| 11 | 2-5 | 23 | 4-6 | 35 | 7-9 |
| 12 | 2-6 | 24 | 4-7 | 36 | 8-9 |

Objective function

The locations of the consumer buildings (nodes) were fixed. The piping network was modeled by a graph with undirected links. Either radial or tree-shaped network or a mixing of both was allowed. The objective was to find the optimal/near-optimal piping network configuration of a district cooling system that minimizes the infrastructure (piping) cost compatible with the minimum pumping energy cost as listed in Eq. (1) below.

$$\min Z = \sum_{i=1}^{n-1} \sum_{j=i+1}^n C_{ij} x_{ij} + \sum_{k=1}^{8,760} \text{Hourly Pumping Cost}_k \quad (1)$$

subject to:

$$\sum_{i=1}^{n-1} \sum_{j=i+1}^n x_{ij} = n - 1 \quad (2)$$

$$\sum_{i \in U} \sum_{j > i} x_{ij} \leq |U| - 1, \quad U \subset V, \quad |U| \geq 2 \quad (3)$$

where

| | | |
|-------------|---|--|
| n | = | number of nodes in the piping network |
| C_{ij} | = | the cost of (i, j) pipe segment = $L_{ij} \times CPUL_{ij}$ |
| L_{ij} | = | pipe length of (i, j) pipe segment |
| $CPUL_{ij}$ | = | cost per unit length of (i, j) pipe segment which depends on the pipe diameter |
| x_{ij} | = | $\in \{0, 1\}$ is the decision variable |

Eq. (2) is true for all valid piping networks in which n nodes must have $n - 1$ links. Inequality (3) states that if there are more than $|U| - 1$ links connecting the nodes of a subset U , this subset U will contain a cycle which is not allowed in this study.

The hourly chilled water demands of each DCS consumer building developed previously are used to determine the pumping cost. Based on a certain piping network generated, the chilled water flow rate along each pipe segment was calculated. Then the diameter of each pipe segment was determined using the chilled water flow rate and a maximum flow velocity of 1.2 m/s. According to the Darcy formula shown in Eq. (4), the pressure drop along each pipe segment could be calculated, and hence the critical path could be identified.

$$h_f = \frac{f l Q^2}{3.03 d^5} \quad (4)$$

where

| | | |
|-------|---|-------------------------|
| h_f | = | head loss |
| f | = | friction factor |
| l | = | pipe length |
| Q | = | chilled water flow rate |
| d | = | pipe diameter |

With the hourly total chilled water flow rate in the network and the pressure head along the critical path, the hourly pumping energy could be determined. The pumping energy was then used to calculate the corresponding pumping cost, which consisted of two components (energy charge and demand charge), making reference to the tariff structure of the China Light & Power Limited in HKSAR (CLP, 2006). The pipe costs of each pipe segment were determined according to their pipe lengths and diameters. Then the sum of the pumping cost and the pipe work cost was equal to the total cost of the piping network that to be minimized.

Local Search/Looped Local Search

GA performs an adaptive and global sampling of the search domain. This type of heuristic algorithm for solving optimization problem can find the nearly optimal solutions within a reasonable amount of computation time. However, it does not refine the solution efficiently. A local search algorithm incorporated into GA can search a better solution, generally starting with a feasible solution found by the crossover/mutation operators. At each iteration, an improving solution may be found by searching the neighborhood of the current solution.

Local search can be applied to each individual candidate in every generation, but it is time consuming and may not be effective. Therefore, in the present study, local search is applied if a local minimum is found, i.e., there is no further improvement for the objective function value after a certain number of generations. Elite is taken as the candidate for local search. There are two types of local search developed, namely Local Search and Looped Local Search, for the present optimization problem. The steps of Local/Looped Local Search for problem of size m are detailed as follows:

Local Search

- i. If the fitness value converges and there is no further improvement by GA operators (crossover & mutation) after x generations (arbitrarily assigned), subroutine "Local Search/Looped Local Search" will be called.
- ii. The elite in the current generation will be taken as the candidate for Local Search/Looped Local Search.
- iii. The longest link ($link_{longest}$) of the elite and the two nodes ($node_{NB}$ and $node_{NE}$) joining this link are identified.
- iv. Take $node_{NB}$ as a searching point and be connected to the other node $_j$, ($j \in \{1, 2, \dots, m\}$, $j \neq NB$ or NE), to form a new $link_{NB-j}$.
- v. The new link: $link_{NB-j}$ replaces the original longest link, $link_{longest}$, to form a new piping network.
- vi. Calculate the fitness value of this new network.
If $fitness\ value_{NB-j} \geq fitness\ value_{elite}$, do nothing.
If $fitness\ value_{NB-j} < fitness\ value_{elite}$, assign a new best fitness value: $fitness\ value_{elite} \leftarrow fitness\ value_{NB-j}$ and $elite \leftarrow new\ solution$.
- vii. Repeat steps iv – vi using other nodes of j ($j \in \{1, 2, \dots, m\}$, $j \neq NB$ or NE) until $j = m$.
- viii. Repeat steps iv – vii using $node_{NE}$ as the searching point.

Looped Local Search

- ix. If there is no further improvement by GA operators (crossover & mutation) and local search after x generations, the second longest link ($\text{link}_{k, \text{longest}}^{(k=2^{\text{nd}})}$) of the elite and the two nodes ($\text{node}_{\text{NB},k}$ and $\text{node}_{\text{NE},k}$) joining the link are identified.
- x. Take $\text{node}_{\text{NB},k}$ as a searching point and be connected to the other node_j , ($j \in \{1, 2, \dots, m\}$, $j \neq \text{NB},k$ or NE,k), to form a new link $\text{link}_{\text{NB},k-j}$.
- xi. The new link: $\text{link}_{\text{NB},k-j}$ replaces the original link, $\text{link}_{k, \text{longest}}$, to form a new piping network.
- xii. Calculate the fitness value of this new network.
 If $\text{fitness value}_{\text{NB},k-j} \geq \text{fitness value}_{\text{elite}}$, do nothing.
 If $\text{fitness value}_{\text{NB},k-j} < \text{fitness value}_{\text{elite}}$, assign a new best fitness value: $\text{fitness value}_{\text{elite}} \leftarrow \text{fitness value}_{\text{NB},k-j}$ and elite \leftarrow new solution.
- xiii. Repeat steps x – xii using other nodes of j ($j \in \{1, 2, \dots, m\}$, $j \neq \text{NB},k$ or NE,k) until $j = m$.
- xiv. Repeat steps x – xiii using $\text{node}_{\text{NE},k}$ as the searching point.
- xv. Repeat steps ix – xiv for $k = (3^{\text{rd}}, 4^{\text{th}}, \dots, m - 1^{\text{th}})$, i.e. the third longest link, fourth longest link,, $m - 1$ th longest link.

ANALYSIS OF SIMULATED RESULTS

The performance of GA without Local Search (base case) versus the case with Local Search and Looped Local Search for a problem of size 17 is shown in Table 2. The minimum, maximum and average values of both the best fitness value and first-hit generation number (the generation number at which the best solution first appears) under the three different cases over 10 runs are listed for comparison. It can be seen that both cases with Local Search and Looped Local Search outperform the base case. Moreover, the case with Looped Local Search gives the best performance, in terms of both solution quality (min.: $2,913 \times 10^6$ and average: $3,128 \times 10^6$) and computational efficiency (min.: 248 and average: 557 (first hit generation no.)).

Table 2 Simulated results over 10 runs for problem of size 17

| Run no. | Without Local Search | | With Local Search | | With Looped Local Search | |
|---------|--------------------------------------|--------------------------|--------------------------------------|--------------------------|--------------------------------------|--------------------------|
| | Best Fitness Value ($\times 10^6$) | First Hit Generation No. | Best Fitness Value ($\times 10^6$) | First Hit Generation No. | Best Fitness Value ($\times 10^6$) | First Hit Generation No. |
| 1 | 3,240 | 953 | 3,014 | 861 | 2,913 | 507 |
| 2 | 3,542 | 840 | 3,273 | 843 | 3,155 | 723 |
| 3 | 3,313 | 991 | 3,425 | 948 | 3,135 | 814 |
| 4 | 3,596 | 908 | 3,161 | 701 | 3,140 | 352 |
| 5 | 3,794 | 893 | 3,079 | 954 | 3,110 | 850 |
| 6 | 3,496 | 827 | 3,374 | 976 | 3,402 | 748 |
| 7 | 3,254 | 841 | 3,637 | 598 | 3,282 | 341 |
| 8 | 3,617 | 941 | 3,171 | 918 | 2,994 | 616 |
| 9 | 3,275 | 919 | 2,994 | 483 | 2,948 | 373 |
| 10 | 3,194 | 723 | 3,233 | 747 | 3,203 | 248 |
| Min. | 3,194 | 723 | 2,994 | 483 | 2,913 | 248 |
| Max. | 3,794 | 991 | 3,637 | 976 | 3,402 | 850 |
| Average | 3,423 | 884 | 3,236 | 803 | 3,128 | 557 |

In both algorithms of Local Search and Looped Local Search, the “length” of the pipe segment is used as a criterion for selecting points (nodes) to construct new link. However, other selecting criteria such as minimum pipe diameter and pipe links along the critical path are also potential factors which can influence the fitness value of the problem. In order to investigate their effects on the GA performance, two more sets of simulations were carried out. For the case using minimum pipe diameter as the selecting criterion, the similar procedures as listed above were used. The $link_{k, \text{longest length}}$ is replaced by $link_{k, \text{min. dia.}}$. For the case with links along the critical path, only the $link_{k, \text{longest length}}$ along the critical path were selected for local search.

The simulated results are listed in Table 3. Both cases of longest length and minimum diameter obtain the minimum fitness value of $2,913 \times 10^6$. The layout of the best piping configuration is plotted in Figure 2. In terms of average fitness value over the 10 runs, the best value of $3,096 \times 10^6$ comes from the case of minimum diameter. However, the case of longest length offers the best computational efficiency, i.e. it takes fewer steps to search the optimal/near-optimal solution. Results from the case of critical path gives the worst performance, which is even worse than the base case.

Table 3 Simulated results over 10 runs for problem of size 17 with 3 types of looped local search

| Run no. | Longest Length | | Minimum Diameter | | Critical Path | |
|---------|--------------------------------------|--------------------------|--------------------------------------|--------------------------|--------------------------------------|--------------------------|
| | Best Fitness Value ($\times 10^6$) | First Hit Generation No. | Best Fitness Value ($\times 10^6$) | First Hit Generation No. | Best Fitness Value ($\times 10^6$) | First Hit Generation No. |
| 1 | 2,913 | 507 | 3,010 | 1,000 | 3,345 | 845 |
| 2 | 3,155 | 723 | 3,279 | 699 | 3,345 | 845 |
| 3 | 3,135 | 814 | 2,937 | 683 | 3,435 | 906 |
| 4 | 3,140 | 352 | 2,999 | 970 | 3,608 | 984 |
| 5 | 3,110 | 850 | 3,200 | 991 | 3,202 | 966 |
| 6 | 3,402 | 748 | 3,144 | 660 | 3,507 | 992 |
| 7 | 3,282 | 341 | 2,913 | 975 | 3,245 | 946 |
| 8 | 2,994 | 616 | 2,991 | 983 | 3,726 | 970 |
| 9 | 2,948 | 373 | 2,977 | 957 | 4,717 | 752 |
| 10 | 3,203 | 248 | 3,514 | 654 | 3,198 | 882 |
| Min. | 2,913 | 248 | 2,913 | 654 | 3,198 | 752 |
| Max. | 3,402 | 850 | 3,514 | 1,000 | 4,717 | 992 |
| Average | 3,128 | 557 | 3,096 | 857 | 3,533 | 909 |

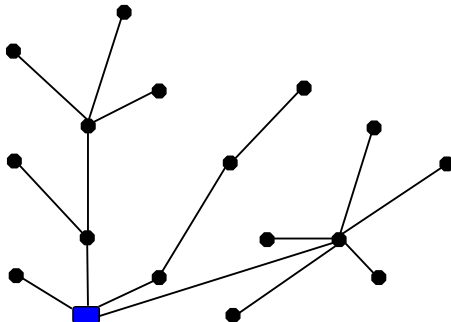


Figure 2. Optimal piping configuration for problem of size 17

CONCLUSION

District cooling system is a mass-scale production of chilled water which is delivered to serve a group of consumer buildings. It can offer both economical and environmental benefits. Because of the substantial capital investment involved, an optimal design of the distribution piping network is one of the crucial factors for successful implementation of the district cooling scheme. However, due to the huge number of different combinations of the piping configuration, it is impractical to evaluate each individual case by exhaustive approach. In the present study, a probabilistic search heuristics, genetic algorithm, was adopted to find the optimal/near-optimal solution of a piping network for a hypothetical site. In order to improve the searching performance, technique of Local Search and Looped Local Search were developed and incorporated into GA during the optimization process. It was found that the Looped Local Search could efficiently improve the search performance.

The results are encouraging that the local search techniques developed can search better solution in the vicinity of a current near-optimal solution. Future work will be followed to pursue further improvement in the performance of GA with local search including choosing candidate, other than the elite, to implement local search procedures; and incorporating constraints in the piping network problems such as obstructions at some locations of the district. It is hoped that the methodology developed in the present study could assist the engineers to design an optimal piping configuration of a DCS more efficiently and effectively.

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