Optimization of Urban Heating Network Design Using Genetic Algorithm

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***Abstract*—As the main energy source is coal burning, district heating in Northern China is an important driver of air pollution. Optimization of the performance of District Heating Network (DHN) carries both social and economic benefits. This study proposes an approach for optimizing urban heating network design based on Genetic Algorithm. Our case study shows that DHN can meet the users' requirements and achieve minimum cost in parallel.**

Keywords*—*optimization, design, District Heating Network, Genetic Algorithm

I. INTRODUCTION

Given the rapid urbanization in China over the last forty years, city-wide District Heating Network (DHN) has been widely applied in Northern China. Annual energy consumption of DHN in Northern China accounted for 24% of total building energy consumption in China in 2013 [1]. Given that nearly 90% of DHN depends on coal as the energy source, coal is a significant driver of air pollution in China [1]. Hence, improving the energy efficiency of DHN carries significant consequences. This can be achieved through improved design, as well as sophisticated maintenance and operation.

Earlier studies on the energy efficiency of DHN focused on two aspects: design and operation. [2] proposed two indicators, "uniformity" and "transmission efficiency", to assess the economic efficiency of DHN. [3] used genetic algorithm to develop single-period and multi-period operational plans for optimized control of district heating and cooling plants. Some studies covered DHN design. [4] built a mixed integer linear programming model to design a district cooling network in a city. Both [5] and [6] used Genetic Algorithm for DHN configuration optimization. However, such algorithms can only address simple networks such as tree networks.

Our study focuses on the design process of DHN. A proper design is important not only because of its decisive effect on energy performance, but also the short-term high-investment and long-term payback-period problem. After determining the topology of the network (the connection of pipelines is mainly based on heating demand, topography, and urban morphology), the next step is to select the diameter of pipes, which is often restricted by many conditional factors and manual control is often preferred. This study develops a method based on Genetic Algorithm (GA) to decide the pipe diameters automatically under given constraints to achieve high performance. This approach can be adopted for both the tree and the ring network of DHN.

II. METHODOLOGY

We formulate an optimization problem as shown in (1) below.

$$\begin{gathered} min\,Cost = f_{cost}(D) \\ s.t. Accessibility \\ User\ demand \\ Network\ structure \\ \Omega(D) = \{d_1, d_2, \dots, d_m\} \end{gathered} \tag{1}$$

where $Cost$ (RMB) is the optimization objective, or the sum of all costs of DHN, including the initial investment and the annual energy consumption converted into money; D (mm) is the selected diameter of the pipelines (a vector), and $Cost = f_{cost}$, a function of D; $Accessibility$ is the first constraint. It is related to D and is a key factor to assess whether heating supply can meet the minimum demands (including flow rate and water pressure) of all users or not [2]; the second constraint is the fixed water temperature. In most DHNs in China, the inlet and outlet water temperatures of the heat source are fixed. Hence, for the end users (building blocks), there are minimum requirements for hot water flow rate and water pressure, which constitute the $User\ demand$; $Network\ structure$ refers to the connection relationship and the length of the pipe; $\Omega(D)$ is the domain of D, which consists of discrete numbers.

(1) is a complex nonlinear optimization problem. There are hundreds of pipelines in one DHN in China. It is extremely hard or even impossible to solve the problem based on existing analytical tools. Evolutionary approaches such as GA may be used to overcome this challenge after some modifications.

A. Constraints: Accessibility Analysis

Since $User\ demand$, $Network\ structure$, and $\Omega(D)$ are given at the current stage of DHN design, this section will analyze the accessibility of DHN. Although the water flow in DHN is a dynamic process, to simplify the problem, only the steady state is considered. However, this study will not consider valves in our accessibility analysis, as valves increase

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energy consumption and the adjustment of valves for hydraulic balance is not the focus of DHN design.

Graph theory is used to build the mathematical model for accessibility analysis [2]. Eq. (2)-(4) show the relationship between the flow rate and the water pressure. There are $n+1$ nodes (representing end-users or cross-points in DHN; one node, the constant pressure point, will be excluded in the following calculation because it is linearly dependent on other nodes) and b edges (representing pipelines) in the network.

$$AG = Q \tag{2}$$

$$A^T P = (S \cdot diag(G) \cdot diag(|G|) - H_p) \tag{3}$$

$$B_f\left(S \cdot diag(G) \cdot diag(|G|) - H_p\right) = \mathbf{0} \tag{4}$$

$$S = f_s(D) \tag{5}$$

where A is an $n \times b$ incidence matrix showing the water flow direction; the $b \times 1$ vector G (kg/s) represents water flow rates of all the pipelines; the $n \times 1$ vector Q (kg/s) is the water leaking rate on every node (which is normally $\mathbf{0}$); the $n \times 1$ vector P (Pa) is the water pressure on every node; the $b \times 1$ vector S (Pa s^2/kg^2) represents the resistance coefficients of all pipes; $diag(G)$ equals $I_{b\times b} \cdot G_{b\times 1}$; the $b \times 1$ vector H_p (Pa) is "pump lifts" of all pipelines (if there is no pump in a line, the element is 0); the $(b-n) \times b$ matrix B_f is the fundamental loop matrix; f_s indicates S is a function of D.

A can be divided into two parts shown in Eq. (6).

$$A = [A^* \ A'] \tag{6}$$

where superscript $*$ represents pipelines without user demand of flow rate and water pressure (those which are connected to end-users in most situations); superscript $'$ means no user demand.

Assuming Q is $\mathbf{0}$, for the sub-network without user demand:

$$A^* G^* = -A' G' \tag{7}$$

Next, accessibility analysis can be carried out. It is not 100% realistic, but an ideal model to test whether the DHN design meets the minimum demand of users.

Assume G' is the user-demanded flow rate.

When A^* represents a tree network (with no loop in it):

$$P = ({A^*}^T)^{-1}(S^* \cdot diag(G^*) \cdot diag(|G^*|) - H_p^*) \tag{8}$$

Calculate P with Eq. (7) and (8), and examine whether water pressure drops for all end-users meet the minimum requirement. If so, this DHN design is "accessible", meaning that it meets the design requirement.

According to Graph Theory, a ring network can be re-configured into a tree network with some independent edges (branches). When A^* represents a ring network (with a loop or loops in it):

$$G^* = B_f^* G_l^* - \begin{bmatrix} (A_t^*)^{-1} \\ \mathbf{0} \end{bmatrix} A' G' \tag{9}$$

$$B_f^*\left(S^* \cdot diag(G^*) \cdot diag(|G^*|) - H_p^*\right) = \mathbf{0} \tag{10}$$

where subscript t represents tree and subscript l represents branch.

With Eq. (9) and (10), G_l^* and G^* can be solved.

Hence, P can be solved using Eq. (11). The next accessibility analysis step is the same as in a tree network.

$$P = ({A_t^*}^T)^{-1}(S_t^* \cdot diag(G_t^*) \cdot diag(|G_t^*|) - H_{p,t}^*) \tag{11}$$

Note that water pump lifts in H_p can be adjusted to make the network "accessible". However, higher pump lifts result in higher energy consumption.

B. Optimization objective

With different focuses, $Cost$ in (1) can appear in different categories For example, if low initial investment is the priority, $Cost$ covers the construction budget. In this article, both initial investment and annual energy consumption will be considered, see Eq. (12).

$$Cost = \frac{PipeCost + PumpStationCost}{DesignedServiceYear} + AnnualEnergyBill \tag{12}$$

where $AnnualEnergyBill$ is strongly related to pump lifts and water flow rates in DHN, and can be calculated using Eq. (2)-(5).

C. Solving the Optimization Problem Using Genetic Algorithm

Genetic Algorithm (GA), inspired by Darwin's theory of evolution, is a random searching algorithm to find the optimal or the near optimal values within a limited time [7]. Fig. 1 shows the GA flowchart for solving the DHN optimization problem in (1).

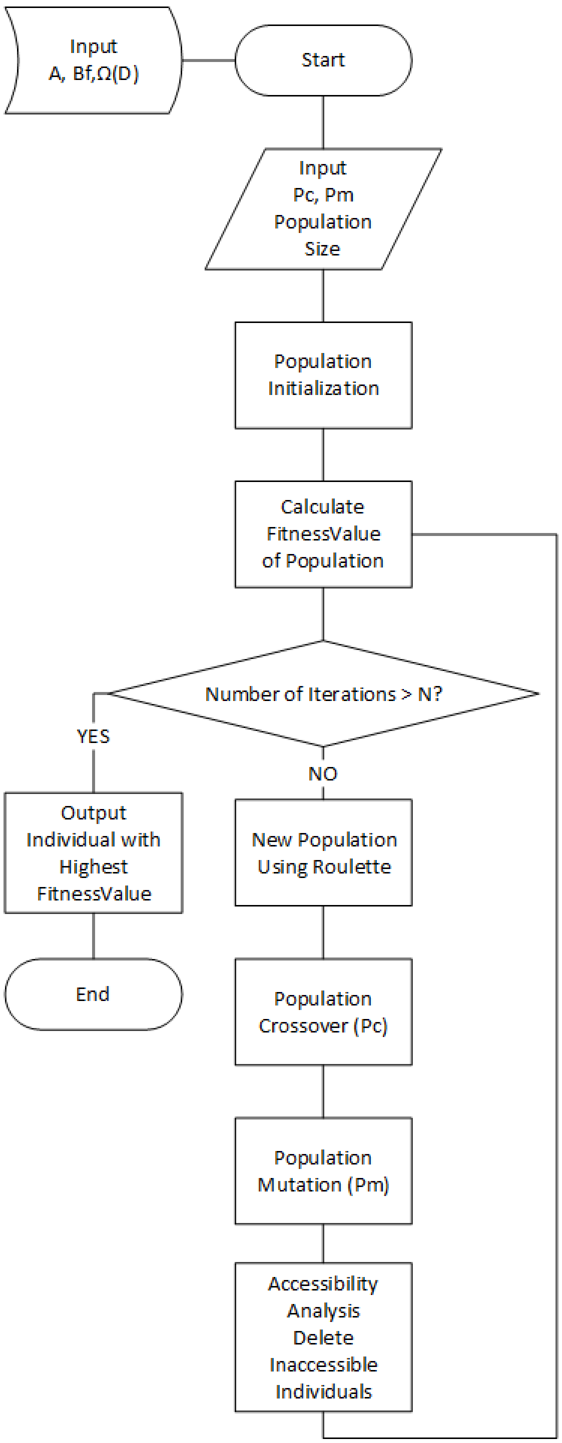

Fig. 1. Flow Chart of Genetic Algorithm

Pc is the probability of crossover variation, while Pm is the probability of mutation.

Population is a matrix. Each row (an individual) is a collection of the diameters of pipelines.

Fitness Value (FV) is the survival probability for an individual in a population. FV is defined in Eq. (13) as follows.

$$FV = \frac{1}{Cost} \tag{13}$$

Roulette is a method to model "survival of the fittest". For individual i, the probability to remain in the new population is:

$$p_{sur} = \frac{(FV)_i}{\sum FV} \tag{14}$$

III. CASE STUDY

Fig. 2 displays the master plan of Sino-Singapore Tianjin Eco-city in Tianjin, China, where the centralized heating area is 12.5 million m^2 with designed heating load of 40W/m^2. A coal burning power plant is situated 40 km away to the north part of the city center, and can serve as the heat source. The temperature of inlet water and outlet water of the heat source are 50°C and 100°C, respectively. The following design is put forward only for simulation study.

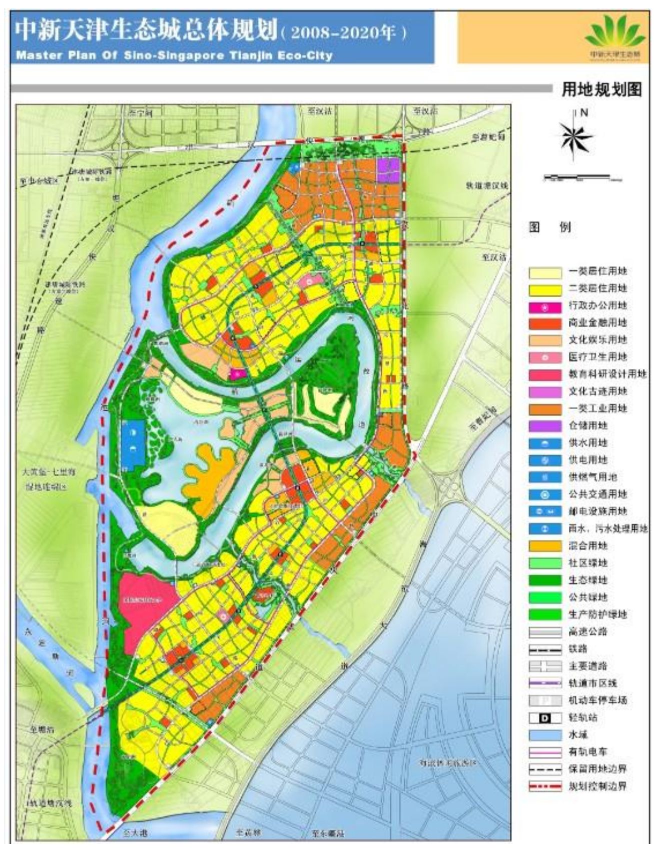

Fig. 2. Master Plan of Sino-Singapore Tianjin Eco-city

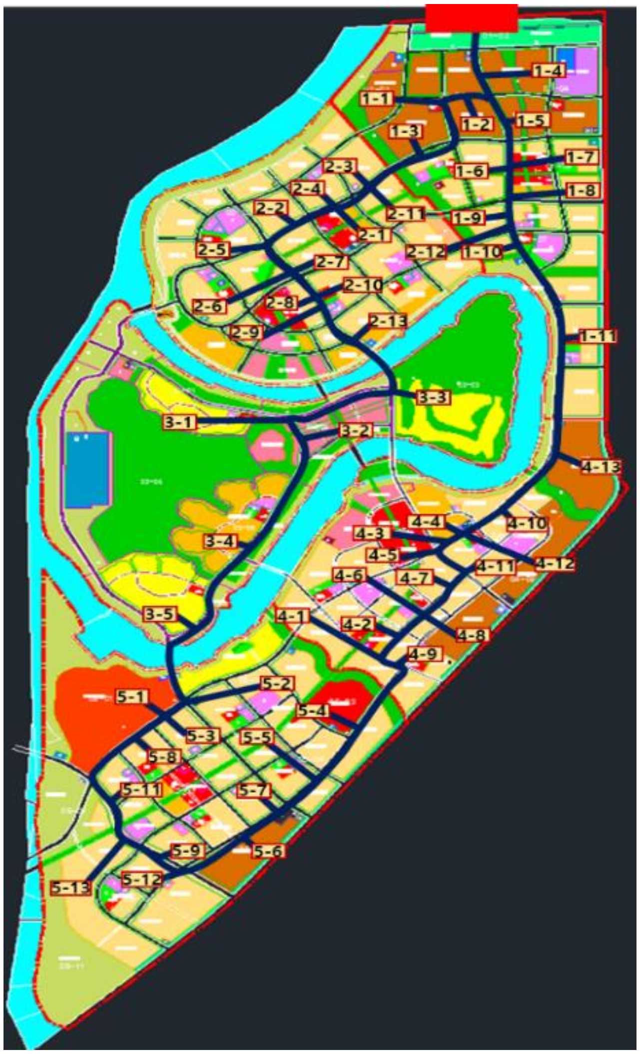

Fig. 3. Geometry of DHN Design for Sino-Singapore Tianjin Eco-city

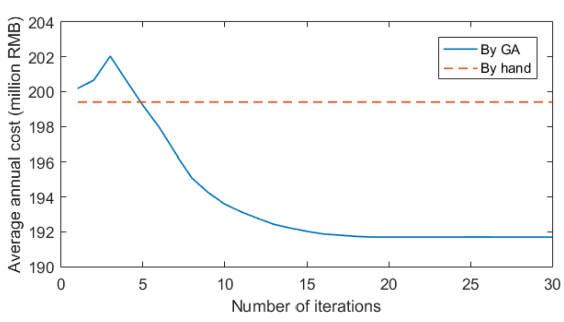

Fig. 4. Optimization Result by Genetic Algorithm and by Hand Calculation

The geometry of the DHN for Sino-Singapore Tianjin Eco-city has been designed, see Fig. 3. The next step is to select the pipe diameters using GA.

Fig. 4 illustrates the result of the GA method. The average annual cost is the mean value of $\frac{1}{FV}(= Cost)$ of all accessible DHN designs (collections of diameters) in one iteration. When we limit the number of iterations to 30, the optimal average annual cost is about RMB192 million, RMB 7.4 million less than the result (RMB 199.4 million) by hand calculation. One thing to be noted, the lowest cost in the 30th iteration was 187 million RMB. If more iterations are performed, better solutions can be found.

V. CONCLUSIONS

This study develops an approach using Genetic Algorithm to optimize the design of DHN for pipe-diameter selection, which is applicable to both tree network and ring network. The optimization objective can be customized to reflect the requirements of the DHN design, such as minimizing the initial construction costs, or maximizing energy conservation. A case study of the DHN design in Sino-Singapore Tianjin Eco-city is made, indicating that this method can reduce cost.

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