APPLYING META-HEURISTIC APPROACH TO OPTIMIZE GAS DISTRIBUTION NETWORK: A CASE STUDY

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ABSTRACT

Design of pipeline, facility, and equipment systems are necessary tasks to configure an optimal natural gas network. Here, a mixed integer programming model is formulated to minimize the total cost in the gas network. Our aim is to determine both locations and types of stations so that location-allocation cost is minimized. We apply the Minimum Spanning Tree (MST) technique to obtain a network with minimum number of arcs, no cycles, spanning all the nodes.

The problem being NP- hard, we propose a meta-heuristic approach and compare its performance with an exact method.

A case study in Mazandaran gas company in Iran is conducted to illustrate the validity and effectiveness of the proposed model and the meta-heuristic approach.

Keyword: Natural-gas network, Minimum Spanning Tree (MST), Meta-heuristic approach

1. INTRODUCTION

Natural gas is one of the most important sources of energy. Exploration, extraction, production, and transportation are stages which natural gas goes through to secure consumers. Due to movement of a large volume of gas at high pressures over long distances, transmission and distribution plannings are basic elements of a natural gas network. While gas pressure is reinforced by compressors in the transmission network, it is reduced by pressure reduction stations in the distribution network. Gas pressure is lessened twice in the distribution network. CGS is defined as a pressure reduction station in which gas pressure is reduced from 1000 psi to 250 psi. In order to maintain the desired gas pressures based on consumers' viewpoints, gas pressure should be fractured for a second time. A TBS is a pressure reduction station reducing gas pressure from 250 psi to 60 psi. Optimal types and locations of pressure reduction stations play key roles in minimizing the total cost in the network. Various topologies of natural gas network exist such as linear, tree-structured, and cyclic. Gas companies usually apply heuristic methods which are based on human's judgment and

experience to find an optimal network. Trial and error procedures are common for such methods. But, for such methods to generate an optimal solution, one often needs an excessive computing work. Optimization methods, however, are suitable tools guaranteeing obtainment of optimal solutions with reasonable computing costs.
Much efforts for optimization of natural gas network have been expended in the past decades. Contesses et al. [1] and Pratt et al. [2] proposed mixed integer programming models for optimization gas operations. Gas flow in natural gas network with the aim to minimize total cost was considered in Wolf et al. [3]. Ruan et al. [4] designed a mainline system for the gas network. This study considered several factors such as pipe size, thickness, pressure, length, etc. Murphy et al. [5] presented a linear programming model to supply gas in a natural gas network.
Several case studies exist on natural gas. Usage of an optimization technique to design a Danish natural gas network was made in Hansen et al. [6]. Design of a genetic algorithm to optimize British gas network was conducted by Boyd et al. [7]. Recently, numerous optimization methods and techniques have been proposed to solve optimization problems in gas networks. Dynamic Programming (DP), Gradient Search (GS) techniques, and meta-heuristic algorithms have received attention in the past decades. Although DP methods find global optimal solutions, but these methods are efficient only for simple networks. GS techniques and meta-heuristic algorithms rarely find global optima. The type of the methods used for solving optimization problems are influenced by problem's nature. Optimization of networks with general structures and with fixed flow rates using DP techniques was presented in Carter [8]. Wilde [9] and Aris et al. [10] optimized gas networks with nonsequential structure using a DP technique. Wu et al. [11] formulated a model for fuel cost minimization. The model employs a GS technique for the gas network. Percell et al. [12] proposed a GS technique for minimization of fuel consumption in gas transmission networks. Complexity of gas network problems necessitates employment of heuristic and meta-heuristic algorithms. Castillo et al. [13] presented an approach for finding economical solutions of distributed gas networks using a genetic algorithm. Chebouba et al. [14] optimized the natural gas pipeline transportation using an Ant Colony Optimization (ACO) algorithm. In [14], the authors proposed an ACO algorithm for the gas pipeline systems having fixed flow rate. The study focused on gas transmission networks where the compressor stations reinforced the gas pressure. The decision variables used in the study were the number of compressor stations and the amount of pressure discharged in each station. The aim of the proposed model was to optimize the consumed power in the network.
The remainder our work is organized as follows. A description of the natural gas network is given in Section 2. In Section 3, we present our proposed meta-heuristic approach. Section 4 discusses a case study conducted in Mazandaran gas company in Iran. Finally, conclusions are given in Section 5.

2. THE PROBLEM

A natural gas network consists of two components: transmission and distribution. Our proposed model is focused on the second component (distribution network) containing several potential locations for the TBS and consumers. A gas distribution network is defined by a set of nodes and a set of arcs. In this network, consumers and the TBS are defined as a set of nodes and connected pipelines are defined as a set of arcs. A tree-structured natural gas network is described for the TBS and consumers. A tree is a connected graph with no cycles and all nodes spanned. Determination of the optimal locations and types of the TBS are decisions to be made by our model to secure consumers' demands. Our model minimizes the total cost in the gas distribution network using the Minimum Spanning Tree (MST) technique.

Formulation

The proposed model considers minimizing the cost of the distribution system and the cost associated with the TBS in the network using the MST technique. The model description follows here.

Notations:

I	= set of candidate TBSs
T	= set of TBS types
Z	= set of consumer/demand zones.

Parameters:

C	= the average cost of piping per distance unit between the TBSs and consumers
CT	= the average cost of piping per distance unit among the TBS
S_t	= establishing cost for TBS of type t
q_z	= demand of consumer zone z
Q_{it}	= capacity of TBS i of type t
d_{iz}	= distance between TBS i and consumer zone z
$d'_{ii'}$	= the distance between TBS i and TBS i'
$d''_{zz'}$	= the distance between consumer zone z and consumer zone z'
M	= a large number.

Decision variables:

$$r_i = \begin{cases} 1, & \text{if TBS } i \text{ is located} \\ 0, & \text{o.w.} \end{cases}$$

$$h_{it} = \begin{cases} 1, & \text{if TBS } i \text{ of type } t \text{ is selected} \\ 0, & \text{o.w.} \end{cases}$$

$$y_{itz} = \begin{cases} 1, & \text{if consumer zone } z \text{ is connected to TBS } i \text{ of type } t \\ 0, & \text{o.w.} \end{cases}$$

$$w_{zz'} = \begin{cases} 1, & \text{if there is a direct link between consumer zone } z \text{ to consumer zone } z' \\ 0, & \text{o.w.} \end{cases}$$

$$u_i = \begin{cases} 1, & \text{if TBS } i \text{ is a root} \\ 0, & \text{o.w.} \end{cases}$$

$$x_{ii'} = \begin{cases} 1, & \text{if there is a direct link between TBS } i \text{ to TBS } i' \\ 0, & \text{o.w.} \end{cases}$$

N_z	= allocated number of consumers to consumer zone z
$f_{ii'}$	= amount of flow from TBS i to TBS i'
$f'_{zz'}$	= amount of flow from consumer zone z to consumer zone z'
$f''_{zz'}$	= amount of gas flow from consumer zone z to consumer zone z'
ew_z	= amount of congested gas flow to be supplied to each consumer

zone z

ew'_{itz} = amount of gas flow from TBS i of type t to consumer zone z.

Objective function:

$\min f = f_1 + f_2 + f_3 + f_4$

where,

$$f_1 = \sum_{i\in I}\sum_{t\in T} h_{it} S_t, \quad (1)$$

$$f_2 = \sum_{i\in I}\sum_{t\in T}\sum_{z\in Z} y_{itz} d_{iz} C, \quad (2)$$

$$f_3 = \sum_{i\in I}\sum_{j\in J} x_{ii'} d'_{ii'} CT, \quad (3)$$

$$f_4 = \sum_{z\in Z}\sum_{z'\in Z} w_{zz'} d''_{zz'} C. \quad (4)$$

Constraints:

$$u_i \le r_i, \qquad \forall i \in I, \quad (5)$$

$$\sum_{i\in I} u_i = 1, \quad (6)$$

$$r_i - M(r_{i'} - 1) \ge x_{ii'}, \qquad \forall i, i' \in I, \quad (7)$$

$$r_{i'} \ge x_{ii'}, \qquad \forall i, i' \in I, \quad (8)$$

$$\sum_{i\in I} x_{ii'} \ge (1 - u_{i'}) + M\,(r_{i'} - 1), \qquad \forall i' \in I, \quad (9)$$

$$\sum_{i\in I} x_{ii'} \le (1 - u_{i'}) - M\,(r_{i'} - 1), \qquad \forall i' \in I, \quad (10)$$

$$\sum_{i\in I} x_{ii'} \le r_{i'}, \qquad \forall i' \in I, \quad (11)$$

$$x_{ii'} \le f_{ii'}, \qquad \forall i, i' \in I, \quad (12)$$

$$f_{ii'} \le x_{ii'} M, \qquad \forall i, i' \in I, \quad (13)$$

$$\sum_{i\in I} f_{ii'} - \sum_{i''\in I} f_{i'i''} \ge ((-u_{i'}M) + 1) + (r_{i'} - 1), \quad \forall i' \in I, \quad (14)$$

$$\sum_{i\in I} f_{ii'} - \sum_{i''\in I} f_{i'i''} \le ((u_{i'}M) + 1) + (r_{i'} - 1), \quad \forall i' \in I, \quad (15)$$

$$\sum_{t\in T} h_{it} = r_i, \qquad \forall i \in I, \quad (16)$$

$$\sum_{z\in Z} y_{itz} \ge h_{it}, \qquad \forall i \in I, \forall t \in T, \quad (17)$$

$$\sum_{z\in Z} y_{itz} \le h_{it} M, \qquad \forall i \in I, \forall t \in T, \quad (18)$$

$$\sum_{z\in Z} w_{zz'} + \sum_{i\in I}\sum_{t\in T} y_{itz'} = 1, \qquad \forall z' \in Z, \quad (19)$$

$$N_z - \sum_{z'\in Z} f'_{zz'} = 1, \qquad \forall z \in Z, \quad (20)$$

$$N_{z'} + M(w_{zz'} - 1) \le f'_{zz'}, \qquad \forall z, z' \in Z, \quad (21)$$

$$N_{z'} - M(w_{zz'} - 1) \ge f'_{zz'}, \qquad \forall z, z' \in Z, \quad (22)$$

$$f'_{zz'} \le w_{zz'} M, \qquad \forall z, z' \in Z, \quad (23)$$

$$f'_{zz'} \ge w_{zz'}, \qquad \forall z, z' \in Z, \quad (24)$$

$$(w_{zz'} - 1)M + (q_{z'} + ew_{z'}) \le f''_{zz'}, \qquad \forall z, z' \in Z, \quad (25)$$

$$(w_{zz'} - 1)(-M) + (q_{z'} + ew_{z'}) \ge f''_{zz'}, \qquad \forall z, z' \in Z, \quad (26)$$

$$f''_{zz'} \le w_{zz'} M, \qquad \forall z, z' \in Z, \quad (27)$$

$$f''_{zz'} \geq w_{zz'}, \qquad \forall z, z' \in Z, \tag{28}$$

$$\sum_{z' \in Z} f''_{zz'} = ew_z, \qquad \forall z \in Z, \tag{29}$$

$$(y_{itz} - 1)M + (q_z + ew_z) \leq ew'_{itz}, \qquad \forall i \in I, \forall t \in T, \forall z \in Z, \tag{30}$$

$$(y_{itz} - 1)(-M) + (q_z + ew_z) \geq ew'_{itz}, \quad \forall i \in I, \forall t \in T, \forall z \in Z, \tag{31}$$

$$ew'_{itz} \leq y_{itz} M, \qquad \forall i \in I, \forall t \in T, \forall z \in Z, \tag{32}$$

$$ew'_{itz} \geq y_{itz}, \qquad \forall i \in I, \forall t \in T, \forall z \in Z, \tag{33}$$

$$\sum_{z \in Z} ew_{itz} \leq Q_{it}, \qquad \forall i \in I, \forall t \in T, \tag{34}$$

$$r_i, h_{it}, y_{itz}, u_i, x_{ii'}, w_{zz'}, \in \{0,1\}, \quad \forall i, i' \in I, \forall t \in T, \forall z, z' \in Z, \tag{35}$$

$$N_z, f_{ii'}, f'_{zz'}, f''_{zz'}, ew_z, ew'_{itz} \geq 0, \qquad \forall i, i' \in I, \forall t \in T, \forall z, z' \in Z. \tag{36}$$

Formulas (1)-(4) are the cost functions corresponding to the location-allocation costs. Constraints (5) indicate that exactly one TBS must be defined as a root. Constraint (6) ensures that there is exactly one TBS as the root in the network. Constraints (7) and (8) show the link between two TBSs. Constraints (9)-(11) impose that each TBS receive exactly one link from other TBSs if it is not the root node. The amount of flow between each TBS i and each TBS i' is represented by constraints (12) and (13). Constraints (14) and (15) guarantee that there be no closed loop in the network. Constraints (16) show that each TBS can adopt only one type when it is selected to service consumers. Constraints (17) and (18) ensure that each TBS covers at least one consumer. Constraints (19) represent that each consumer receives service from one consumer or one TBS. Constraints (20) determine the allocated number of consumers to consumer zones. Constraints (21)-(24) express the flow between two consumers. Constraints (25)-(28) represent the amount of gas flow from consumer zone z to consumer zone z'. Constraints (29) indicate the amount of congested gas flow for supplying other consumers by each consumer. Amount of gas flow from TBS to consumer is shown by constraints (30)-(33). Capacity restriction is shown by constraints (34). Constraints (35) impose that the variables be binary. Non-negativity of the variables is represented by constraints (36).

3. THE PROPOSED META-HEURISTIC APPROACH

Meta-heuristic algorithms are designed for solving optimization problems, taking their inspiration from nature.

The meta-heuristic algorithms are usually based on population and memory. A population-based approach produces different cycles in the algorithm. Each cycle contains a number of solutions. A memory-based approach saves the obtained information in each cycle. So, each cycle uses the obtained information in the previous cycles and gains solutions better than the previous ones. The algorithm cleans up the produced solutions at the end of each cycle.

There are essential elements to be considered in the design and implementation of a meta-heuristic algorithm. The elements are:

A solution generation mode.

Stopping conditions.

Here, the proposed meta-heuristic algorithm is presented as follows.

A Meta-heuristic algorithm.

Initialize maxiter and other parameters.
Set noiter = 0.
Generate a solution x using a construction procedure.
Set $x^* = x$.
repeat
    Compute x using a construction procedure.
        if $f(x) \leq f(x^*)$ then
            set $x^* = x$.
            end if
                noiter = noiter+1.
    until stopping condition is met (i.e., noiter=maxiter)

Note that at the initial step, the parameters are initialized. Maxiter is used in the stopping condition for the proposed algorithm. At the second step, a construction procedure is used to form a solution. Then, fitness function ($f(x)$) is evaluated. A fitness function for the proposed meta-heuristic algorithm contains two types of costs. The costs are:

Establishing cost for TBS with respect to its type

The cost of piping among the nodes

At the next cycles, if the fitness function is better than previous one, a previous solution is removed and replaced with new one.

4. A CASE STUDY

A natural gas network case study of Mazandaran gas company in Iran is conducted to verify the proposed model. Surveying on this case, nine potential locations for the TBS were decided. TBSs are selected to secure 39 consumers having definite demands. Consumers' demands are presented in Table 1. Three types of TBSs with different capacities exist in the network. Table 2 represents the establishing cost and capacity of different TBSs. We use the Minimum Spanning Tree (MST) technique to find a spanning tree in the network with a minimal total distance of the links. The average cost of piping per distance unit between the TBSs and consumers is considered to be 25180 units. The average cost of piping per distance unit among the TBS is considered to be 38000 units.

Table 1. Consumers' demands

Con	D	Con	D
1	**211.9**	21	**103.5**
2	**153.3**	22	**125**
3	**110.1**	23	**114.3**
4	**649**	24	**351**
5	**114.5**	25	**222.8**
6	**196.5**	26	**135.4**
7	**210**	27	**117.9**
8	**111**	28	**168.7**
9	**105.8**	29	**325.7**
10	**138**	30	**119.1**
11	**142.4**	31	**100.4**
12	**105.7**	32	**220**
13	**131.2**	33	**352**
14	**180.9**	34	**228.8**
15	**100**	35	**191**
16	**138.6**	36	**116.4**
17	**155.9**	37	**242.6**
18	**117.1**	38	**465.5**
19	**143.8**	39	**167.5**
20	**104.9**		

Table 2. The establishing cost and capacity of the different TBSs

TBS types	Capacity (m3/h)	Cost (unit)
TBS 1	5000	50000000
TBS 2	10000	65000000
TBS 3	20000	85000000

We applied CPLEX 11.0 software package to facilitate computations in our Mixed Integer Programming (MIP) model. This software is based on an exact method (branch and cut). The results showed that only one TBS of type two is selected (No. 3) to secure the total sum of consumers' demands. The objective function for the optimal solution is 276581924.86 units in 12844.53 seconds. Due to complexity of our model, a meta-heuristic approach proposed. The test problems produced to show the validity and effectiveness of our proposed algorithm. The results showed that our proposed meta-heuristic approach is effective for solving the problems. The algorithm obtains good solutions in reasonable times. In comparison with the exact method, the algorithm obtains solutions being closer to the optimal solutions with much less times than the time needed to be spent for obtaining exact optimal solution.

The computational test was developed on a personal computer with Intel (R) Pentium (R) Dual with 2.2 GHz CPU / 4 GB RAM. The algorithm was coded using MATLAB R2009 software package.

5. CONCLUSIONS

We designed an optimal gas distribution network containing pressure reduction stations and consumers. Our aim was to determine optimal locations and types of the TBS so that location-allocation costs were minimized. For this, the Minimum Spanning Tree (MST) technique was applied. A mixed integer programming model for the gas distribution network was formulated. We used the actual data on Mazandaran gas company in Iran to conduct a case study. Our exact optimal results were obtained applying CPLEX 11.0 software package. A meta-heuristic approach was proposed to overcome complexity of our model.

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