A New Mathematical Model To Optimize A Green Gas Network: A Case Study

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1. INTRODUCTION

Regarding the development of gas industry in the recent decades, gas pipeline networks have evolved into huge and complex systems. Exploration, extraction, production, and transportation are stages which natural gas goes through to secure consumers. The network contains three phases. The transmission of gas from central production facility to City Gate Station (CGS) is called a transmission phase, while forwarding gas from CGS to Town Board Station (TBS) is called a feeding phase. Securement of gas to consumers is performed in the distribution phase, where TBS is responsible for supplying the desirable gas pressure based on consumer’s viewpoint. Due to the movement of a large volume of gas at high pressures over long distances, transmission and distribution planning 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.

Pipelines in a natural gas network must be designed based on gas flow rate, length of pipe, gas maximum pressure drop allowance, and gas maximum velocity allowance. 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. Integration of gas network with the issue of environment protection confirms sharp decline in pollution problem. Research on this approach has received considerable attention recently and led to the creation of new research agenda: green gas chain management. So, this concept is a new paradigm the gas chain will have a direct relation to the environment. Nowadays, most research on green gas network has had a tendency to the transmission phase such as researches done by Azadeg et al. [1], Pishvavee and Razmi [2], Jamshidi et al. [3], Kashani and Molaei [4] and Subramanian et al. [5]. These studies focused on transmission of gas and only formulated models corresponding to this field. Hamed et al. [6] presented an integrated multi-period optimization model for the distribution planning in different stages of natural gas.
supply chain. They formulated a mixed integer nonlinear programming. Domschke et al. [7] considered networks containing pipes and various other components like compressor stations and valves with the aim to minimize the running costs of the compressor stations. Borraz-Sanchez and Haugland [8] proposed a solution method based on dynamic programming to address the fuel cost minimization problem to transport natural gas in a general class of transmission networks. Wu et al. [9] formulated a model for fuel cost minimization. The model employs a gradient search technique for the gas network. The steady state behavior of a sample gas distribution network was presented by Taherinejad et al. [10]. Mozafari and Lahroodi [11] presented an Artificial Neural Network (ANN)-based modeling technique for prediction of outlet temperature, pressure and mass flow rate of gas turbine combustor. Aryanejad and Ghaavampour [12] proposed two stage multiple attribute decision making problem in Iranian Gas Distribution Systems. The purpose of their research is to present the possibility of replacing physical unit cost in transportation or distribution problems by an aggregate coefficient, getting qualitative and subjective considerations involved.

Reviewing the literature on gas network design, it is concluded that only a few research papers have considered green gas network. None of these research papers focuses on distribution phase of gas network. In this study, we extend Mohajeri et al. [13-15] model to protect the environment. In addition to managing properly gas distribution network to reduce negative impact of greenhouse gases emissions, we suggest a strategy for achieving an expected goal, simultaneously. Here, we focus on a different and important aspect of green gas network: we focus on pipelines and TBSs selection as a way to reduce emissions. For this, in addition to minimizing the total cost in the whole gas chain, we consider a regulation to reduce GHG emissions coming from gas flow. The proposed mechanism is a constraint on emissions. In this study, we pursue this scenario and develop problem formulation for it corresponding to the regulation. Overall, our main original contribution proposed in this paper is that we present the linear model based on Mohajeri et al’s model to construct an optimal green gas distribution network and propose the Hybrid GA/SA algorithm to solve the large size problems. Here, we intend to conduct a case study of the natural gas network in Mazandaran Gas Company in Iran. To our knowledge, this study is the first paper which decides on the emissions of GHG. In other words, none of the above mentioned activity considers the green gas network in which the emission of GHG is a decision variable. Moreover, none of these research papers focuses on distribution of gas between TBSs and consumers. All of these aspects are covered in this research.

The reminder of this paper is organized as follows: Section 2 represents Problem definition and mathematical model formulation. Section 3 is dedicated to solution methodology and section 4 represents case study. Finally, section 5 signifies the conclusion.

2. PROBLEM STATEMENT

2.1. Description

Here, we focus on the green gas distribution network comprising of the pipelines having various sizes, TBSs, and consumers. The pipeline and TBS belong to the two indispensable components. The pipeline is responsible to connect the two places and to transmit a gas between them, while the TBS provides the motive force to maintain the natural gas flow through the network systems. In this study, we design a green gas distribution network with the aim of both minimizing the total cost and reducing the environmental impact in the whole chain by choosing the optimal locations of the TBSs, the flows of gases, and the pipe diameter sizes along a distribution stage when the demands of customers are given. Figure 1 shows a schematic view of the proposed green gas network.

We use IPCC [16] equations to estimate fugitive emissions as shown below:

\[ E_{gas,industry segment} = A_{industry segment} \times EF_{gas,industry segment} \] (1)

\[ E_{gas,industry segment} = \sum E_{gas,industry segment} \] (2)

where:

- \( E_{gas,industry segment} \) Annual emissions (Gg).
- \( EF_{gas,industry segment} \) Emission factor (Gg/unit of activity).
- \( A_{industry segment} \) Activity value (units of activity).

The indicative factors presented in Table 1 is used to specific classification of emission factors.

![Figure 1. Schematic view of the proposed green gas network](image-url)
TABLE 1. Classification of emission factors of natural gas

<table>
<thead>
<tr>
<th>Facilities</th>
<th>Activity data</th>
<th>Yearly emission factors</th>
<th>Units of Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulator Stations</td>
<td>Number of stations</td>
<td>1000</td>
<td>5000</td>
</tr>
<tr>
<td>Distribution</td>
<td>Length of distribution network</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Gas Use</td>
<td>Number of gas appliances</td>
<td>2</td>
<td>5</td>
</tr>
</tbody>
</table>

2.2. Formulation
Here, a mathematical programming model is proposed. To formulate a mixed integer linear programming (MILP) optimization model mathematically, the following notations are necessary:

2.2.1. Notation
I Set of candidate TBSs
T Set of TBS types
Z Set of consumer/demand zones

2.2.2. Parameters
C The cost of piping per distance unit with respect to gas flow rate
CT The average cost of piping per distance unit among the TBSs
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_{iz}' The distance between TBS \( i \) and TBS \( i' \)
d_{zz}' The distance between consumer zone \( z \) and consumer zone \( z' \)
M A large number.
EF1 Emission factor for pipelines
EF2 Emission factor for TBS
ME Maximum allowable Annual emissions

2.2.3. Variables
\( r_i \) \{1, if TBS \( i \) is located, 0, o.w.
\( h_{it} \) \{1, if TBS \( i \) of type \( t \) is selected, 0, o.w.
\( y_{it} \) \{1, if consumer zone \( z \) is connected to TBS \( i \) of type \( t \), 0, o.w.
\( w_{zz'} \) \{1, if there is a direct link between consumer zone \( z \) to consumer zone \( z' \), 0, o.w.

2.2.4. Objective Function

\[

data \min f = f_1 + f_2 + f_3 + f_4
\]

where,

\[
f_1 = \sum_{i \in I, t \in T} h_{it} S_t
\]

\[
f_2 = \sum_{i \in I, i' \in I} \sum_{z \in Z} y_{it} d_{iz} C
\]

\[
f_3 = \sum_{i \in I, j \in I} x_{ij} d_{ij} CT
\]

\[
f_4 = \sum_{z \in Z, z' \in Z} w_{zz'} d_{zz'} C
\]

2.2.5. Constraints

\[
u_i \leq r_i, \quad \forall i \in I.
\]
\[
\begin{align*}
\sum_{i \in I} y_{i'} &= 1, \\
\eta_i - M (\eta_i' - 1) &\geq x_{i'}, \quad \forall i, i' \in I, \\
\eta_i' &\geq x_{i'}, \quad \forall i, i' \in I, \\
\sum_{i \in I} x_{i'} &\geq (1 - u_i') + M (\eta_i - 1), \quad \forall i' \in I, \\
\sum_{i \in I} x_{i'} &\leq [(1 - u_i') - M (\eta_i - 1)] + (1 - 1 - 1), \quad \forall i' \in I, \\
h_{i} &= 1, \quad \forall i \in I, \\
\sum_{z \in Z} y_{iiz} &\geq h_{i}, \quad \forall i \in I, \forall i' \in T, \\
\sum_{z \in Z} y_{iiz} &\leq h_{i}M, \quad \forall i \in I, \forall i' \in T, \\
\sum_{z \in Z} w_{zi'} + \sum_{i \in I} \sum_{z \in Z} y_{iiz} &= 1, \quad \forall z, z' \in Z, \\
N_z - \sum_{z' \in Z} f_{zi'} &= 1, \quad \forall z \in Z, \\
m_z + M (w_{zi'} - 1) &\leq f_{zi'}, \quad \forall z, z' \in Z, \\
m_z - M (w_{zi'} - 1) &\geq f_{zi'}, \quad \forall z, z' \in Z, \\
f_{zi'} &\leq w_{zi'}, \quad \forall z, z' \in Z, \\
f_{zi'} &\geq w_{zi'}, \quad \forall z, z' \in Z.
\end{align*}
\]

Equations (4)-(7) are the cost functions corresponding to the location-allocation costs. Constraint (8) indicates that exactly one TBS must be defined as a root. Constraint (9) ensures that there is exactly one TBS as the root in the network. Constraints (10) and (11) show the link between two TBSs. Constraints (12)-(14) 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 TBS i' is represented by constraints (15) and (16). Constraints (17) and (18) guarantee that there is no closed loop in the network. Constraint (19) shows that each TBS can adopt only one type when it is selected to service consumers. Constraints (20) and (21) ensure that each TBS covers at least one consumer. Constraint (22) represents that each
consumer receives service from one consumer or one TBS. Constraint (23) determines the allocated number of consumers to consumer zones. Constraints (24)-(27) express the flow between two consumers. Constraints (28)-(31) represent the amount of gas flow from consumer zone z to consumer zone z'. Constraint (32) indicates the amount of congested gas flow for supplying other consumers by each consumer. The amount of gas flow from TBS to consumer is shown by constraints (33)-(36). Capacity restriction is shown by constraint (37). Constraints (38)-(40) express the emission from pipelines and TBSs. Constraint (41) ensures that proposed network yearly emissions is less than Maximum allowable annual emissions. Constraint (42) imposes that the variables be binary. Non negativity of the variables is represented by constraint (43).

3. SOLUTION METHODOLOGY

Our proposed model is based on minimum spanning tree (MST) method which belongs to the NP-hard class of problem (Garey and Johnson) [17]. Due to the complexity of these problems, exact methods need excessive computation time. So, heuristic and metaheuristic algorithms are essential tools for solving such problems in reasonable amounts of time.

Here, the proposed hybrid GA/SA algorithm is presented as follows:

1. Initialize GA parameters and SA parameters (nPop,MaxIt,Cper,Mper;T0,Alpha,MaxIt1,MaxIt2)
2. Initialize SA_Database
3. For Number of possible combinations of TBS
   3.1. Initialize GA population based on MST and calculate related costs and stored in GA_Database
   3.2. While Iteration< Maximum Generations
      3.2.1. Apply crossover and calculate new child's costs and stored in Cross_Database
      3.2.2. Apply Mutation and calculate mutate costs and stored in Mu_Database
      3.2.3. Combines GA_Database, Cross_Database, Mu_Database and sort them according to FITNESS-FN
      3.2.4. Truncated extra members
   END While 3.2
3.3. Choose the best solution of GA
3.4. Initialize T,T0,Alpha,MaxIt1,MaxIt2 for Simulate Annealing algorithm
   3.4.1. BestSol= best solution of GA
   3.4.2. While It1< MaxIt1
   3.4.3. While It2< MaxIt2
   3.4.4. X.Sol=Create neighbor solution of the BestSol and calculate related costs(X.Cost) if (X.Cost< BestSol.Cost) & (Total Emission<ME)
      3.4.5. BestSol= X
      3.4.6. delta=X.Cost- BestSol.Cost;
         p=exp(-delta/T)
         a=rand (0,1)
         if a<p
         BestSol=X
      END if
   END if
   END While It1
3.4.5. T=T^* Absorption rate
   END While It2
3.5. Store BestSol in SA_Database
   END for Number of possible combinations of TBS (until terminating condition)

Return the Best Solution that stored in SA_Database and show related results and graphs

4. 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 119 consumers demands which is 11195 m³/h. Velocity and gas pressure were considered to be 20 m/sec and 30 psi, respectively. We applied GAMS 23.2 software package to facilitate computations in our Mixed Integer Programming (MIP) model and MATLAB R2015 software package for metaheuristic algorithm. The General Algebraic Modeling System (GAMS) is a high level modeling system for mathematical programming and optimization and is specially designed for modeling linear, nonlinear, and mixed integer optimization problems. The system is specially useful with large and complex problems [18]. All the required information we used are as follows:

- Relationships among gas flow rates and pipe diameter sizes.
- The cost of piping per distance unit with respect to the gas flow rate.
- Consumers’ demands.
- The establishing cost and capacity of different TBSs.
- Distance between the TBS and consumers, among the TBSs and among the consumers.

The validity of proposed model is measured for gas distribution network case study of Mazandaran Gas Company as summarized in Table 2. Now, the validity and effectiveness of the proposed metaheuristic algorithm in comparison to the exact method is analyzed. The results are given in Table 3. The results show that our proposed algorithm is effective for solving the problems. To find out that the algorithm obtains good solutions in reasonable times or not we generate 3 large size test problem and the results are given in Figure 2 and Table 4. In comparison to the exact method, the algorithm obtains solutions closer to the optimal solutions with much less time than the time needed to be spent for obtaining exact optimal solution.

4.1. Parameter Tuning

Parameter tuning plays a key role for the algorithm to produce desirable solutions. First, we introduce several levels for each parameter. A different combination of parameter’s levels is defined as a test plan. Then, the test plans are implemented to determine a suitable level for each parameter.
TABLE 2. Optimal Solution

<table>
<thead>
<tr>
<th>Selective path</th>
<th>Amount of gas flow</th>
<th>Pipe (type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-4[1]</td>
<td>5538.1</td>
<td>6&quot;</td>
</tr>
<tr>
<td>5-6[2]</td>
<td>1095.3</td>
<td>110 mm</td>
</tr>
<tr>
<td>5-7[3]</td>
<td>1536.9</td>
<td>125 mm</td>
</tr>
<tr>
<td>5-8[4]</td>
<td>3024.69</td>
<td>160 mm</td>
</tr>
<tr>
<td>3-2[1]</td>
<td>912.4</td>
<td>110 mm</td>
</tr>
<tr>
<td>3-1[2]</td>
<td>623</td>
<td>90 mm</td>
</tr>
<tr>
<td>4-3[3]</td>
<td>1971.2</td>
<td>125 mm</td>
</tr>
<tr>
<td>4-5[4]</td>
<td>1663.8</td>
<td>125 mm</td>
</tr>
<tr>
<td>8-9[5]</td>
<td>2079</td>
<td>160 mm</td>
</tr>
<tr>
<td>9-10[6]</td>
<td>1312.39</td>
<td>110 mm</td>
</tr>
<tr>
<td>10-11[7]</td>
<td>817.09</td>
<td>110 mm</td>
</tr>
</tbody>
</table>

Objective: 217391366.76
Annual Emission: 10008.3 (m³/yr)

TABLE 3. Computational results

<table>
<thead>
<tr>
<th>NUM.</th>
<th>No. of TBS</th>
<th>No. of Consumer</th>
<th>Proposed Algorithm (Hybrid GA/SA)</th>
<th>Exact Model (GAMS)</th>
<th>GAP (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>5</td>
<td>1.09E+08</td>
<td>108500385.5</td>
<td>4.71E-03</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>5</td>
<td>1.15E+08</td>
<td>114572467.6</td>
<td>4.70E-03</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>7</td>
<td>1.47E+08</td>
<td>145523793.2</td>
<td>6.88E-03</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>7</td>
<td>1.60E+08</td>
<td>158309288.5</td>
<td>7.68E-03</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>6</td>
<td>1.17E+08</td>
<td>116935096.6</td>
<td>9.04E-04</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>6</td>
<td>1.35E+08</td>
<td>134250942.2</td>
<td>5.88E-03</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>9</td>
<td>1.67E+08</td>
<td>165620613.6</td>
<td>8.76E-03</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>9</td>
<td>1.85E+08</td>
<td>183824992.5</td>
<td>6.78E-03</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>11</td>
<td>2.18E+08</td>
<td>21731385.8</td>
<td>2.91E-03</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>11</td>
<td>2.20E+08</td>
<td>218733880.6</td>
<td>5.89E-03</td>
</tr>
</tbody>
</table>

The levels of parameters are given as follows:
- Initial population: 2 levels (40,50)
- Crossover rate: 3 levels (0.2,0.3,0.4)
- Mutation rate: 2 levels (0.1,0.2)
- Max Generation: 2 levels (100,200)
- Initial temperature: 3 levels (300,400,500)
- Absorption Rate: 2 levels (0.955,0.99)

The test plans are implemented to determine a suitable level for each parameter. The test problems are given as follows:
- One TBS and five consumers
- Two TBS and seven consumers
- Three TBS and six consumers
- Four TBS and nine consumers

Each test plan is implemented for each defined test problem and the obtained results are saved using the following relation:

\[
GAP = \frac{Algorithm Optimal - Optimal}{Optimal} \times 100
\]

(44)

Figure 2. The results of large test problem (9 TBS & 39 CONS)

TABLE 4. The necessity of using proposed algorithm

<table>
<thead>
<tr>
<th>Num</th>
<th>Test Problem Tbs &amp; Consumer</th>
<th>Total Demand (m³/h)</th>
<th>Total Cost/Elapsed Time</th>
<th>Gap (%)</th>
<th>Annual Emission (m³/Yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>9 &amp;15</td>
<td>4215.2</td>
<td>1.57E+08 296507.63 sec</td>
<td>1.30E-06</td>
<td>11316.9</td>
</tr>
<tr>
<td>12</td>
<td>9 &amp;20</td>
<td>4979.3</td>
<td>1.74E+08 456989.14 sec</td>
<td>1.02E-07</td>
<td>12248.7</td>
</tr>
<tr>
<td>13</td>
<td>9 &amp;39</td>
<td>7188.2</td>
<td>2.15E+08 695804.13 sec</td>
<td>1.16E-06</td>
<td>13792.1</td>
</tr>
</tbody>
</table>
Design Expert10 software package is applied to analyze the impact of different parameters on gap value. The results are shown in Figure 3. Corresponding to the obtained results, levels 50, 0.2, 0.1, 200, 500 and 0.95 were selected for Initial population, Crossover rate, Mutation rate, Max Generation, Initial temperature and Absorption Rate, respectively.

Here, we compare the results of our study with Mohajeri et al’s and Mazandaran Gas Co as we show in Figures 4 and 5.

The results of comparing this study with Mohajeri et al’s study:

- The algorithm that proposed in this study is 15 times faster.
- In this study Annual emissions is 6.3% less than Mohajeri et al.
- Total cost of this study is 0.2% more than Mohajeri et al, Due to In terms of the environmental restrictions.

Details are given in Table 5.

The results of comparing this study with Mazandaran Gas Co. study:

- The algorithm that proposed in this study is extremely faster than Mazandaran Gas Co.
- In this study, Annual emissions is 66% less than Mazandaran Gas Co.
- Total cost of this study is 52% less than Mazandaran Gas Co.

Details are given in Table 6.

5. CONCLUSIONS

In this paper, an optimal mathematical green gas network was established based on the Mohajeri et al’s model. The model considered all factors influencing the total cost of a gas network such as pipe diameter, length of pipe, etc.
We also considered environmental impact of our proposed gas distribution network to achieve sustainable development. For this, in addition to minimizing the total cost in the whole gas chain, we considered a regulation to reduce GHG emissions coming from gas flow. The proposed mechanism was a constraint on emissions. In this study, we pursued this scenario and developed problem formulation for it corresponding to the regulation. Overall, our main original contribution proposed in this paper was that we presented the linear model to construct an optimal green gas distribution network and proposed the Hybrid GA/SA algorithm to solve the large size problems. To our knowledge, this study is the first paper which decides on the emissions of GHG. We also used the actual data on Mazandaran Gas Company in Iran to conduct a case study. Optimal results were obtained applying GAMS 23.2 software package. Due to the inability of this software to provide solutions for large size problems in a reasonable time, the metaheuristic algorithm was proposed. As a result, with the proposed algorithm, we obtained excellent results. This will enable us to design a fast, effective and robust decision aid tool based on the suggested model.

There remain many open problems to be further investigated. We conclude this paper by discussing future research directions, which we hope will be a helpful guide to interested readers.

For future research, this problem can be presented in a multi-objective form. Because the computational time increases significantly when the size of the problem increases, developing an efficient exact or heuristic solution method is also a critical need in this area. Thus, it would be interesting to propose exact solution methods, such as Benders’ decomposition method, to partition the structure of the model into small problems.

6. REFERENCES


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چکیده

کربن درهم کردن یک شبکه سبز، به ترتیب حجم زیادی از گازهای گلخانهای منتشر شده ایجاد شده است. به همین علت، مساله شبکه گازرسانی سبز نیاز به توجه بیشتری در دهه‌های اخیر پیدا کرده است. در این مقاله الگوریتم‌های بهینه سازی به عنوان یک محدودیت زیست محیطی در نظر گرفته شده است. در همین محیط، یک مدل بهینه سازی برای شبکه گاز، که در آن انواع گازهای گلخانهای بعنوان یک محدودیت زیست محیطی مطرح و مورد بررسی قرار گرفته است. در این مقاله یک شبکه گازی با هدف و نیازهای زیست محیطی و حفاظت از محیط زیست برای رسیدن به توسعه پایدار فرموله شده است. جهت حل مدل با دقت بالا در ابعاد کوچک و متوسط، از نرم‌افزار GAMS استفاده گردیده است. نتایج نشان می‌دهد که الگوریتم پیشنهادی قادر به ارائه حداکثر بهترین و سریع‌تر برای مسائل با ابعاد بزرگ می‌باشد. مطالعه موردی شرکت گاز استان مازندران در ایران به‌عنوان نشان دهنده اعتبار و اثربخشی روش پیشنهادی انجام شده است.