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A Multi objective Optimization Method for Simulating the Operation of Natural gas Transport System

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ABSTRACT

The optimization of gas pipeline networks plays a pivotal role in ensuring the efficient and economically viable transportation of natural gas. In this research, we have developed a comprehensive mathematical model capable of analyzing diverse network configurations, encompassing both linear and branched topologies. Our scientific investigation aims to explore the optimization potential of gas pipeline networks, employing a sophisticated and systematic approach to enhance network design and operation. The overarching objective is to achieve maximum efficiency and reliability in gas delivery to customers. The optimization process focuses on minimizing power requirements, maximizing gas flow rate, minimizing the fuel consumption, and maximizing line pack to ensure the optimal utilization of the pipeline infrastructure. To accomplish these objectives, our study employs advanced mathematical models that accurately depict network behavior, cutting-edge simulation tools to explore various operational scenarios, and state-of-the-art optimization algorithms to identify the most favorable network configuration and operating conditions. To facilitate this optimization process, we have incorporated the VIKOR (**VI**ekriterijumsko **KO**mpromisno **R**angiranje) method, a potent multi-criteria decision-making technique. Through the application of this approach to two case studies, we have demonstrated its effectiveness in identifying optimal network configurations. Furthermore, we have conducted an analysis to determine the total cost and fuel consumption associated with different network configurations, offering valuable insights for decision-making purposes. The results of our study underscore the superiority of our approach in identifying more economical networks compared to existing methods. By embracing the proposed approach, gas transportation networks can be optimized to achieve superior cost-efficiency and reduced fuel consumption.

Keywords: Gas transportation, multi-objective optimization, VIKOR method, mathematical modeling, MCDM, Line pack.

1. INTRODUCTION

The transportation of natural gas via pipeline systems plays a pivotal role in the energy infrastructure of numerous nations globally. In recent years, there has been an increasing

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emphasis on acknowledging the importance of natural gas as a greener alternative to traditional fossil fuels. Consequently, many countries are making substantial investments in the expansion of their gas pipeline networks to cater to the escalating demand for this valuable resource.

In the context of optimizing gas pipeline networks to improve their operational effectiveness and efficiency, various network types can be categorized based on their purpose and configuration. One classification focuses on the intended uses of the networks, including:

a) Long-distance transmission pipelines: These pipelines are responsible for transporting natural gas over extensive distances, connecting production sites to major urban areas, industrial hubs, and power generation facilities. Spanning hundreds or even thousands of kilometers, these pipelines are typically designed to operate at high pressures, aiming to minimize energy losses during the transportation process [1].

b) Distribution pipelines play a vital role in the transportation of natural gas to end-users in residential, commercial, and small industrial sectors. These pipelines are characterized by relatively smaller dimensions and operate at lower pressure levels compared to transmission pipelines. Their primary function is to supply natural gas to local distribution companies or utilities, which subsequently distribute it to end-users through a network of interconnected local distribution lines[2].

c) Gathering pipelines have a critical role in the collection of natural gas from multiple production wells and the efficient transportation of the gathered gas to processing plants or transmission pipelines. These pipelines are primarily located in rural areas and operate at lower pressure levels compared to transmission and distribution pipelines. Their function is to facilitate the movement of natural gas from various production sources to the subsequent stages of processing and transmission, ensuring a reliable supply for further utilization [3].

d) Offshore pipelines play a pivotal role in the transportation of natural gas from offshore production sites to onshore facilities or directly to the market. These specialized pipelines are meticulously engineered to endure the challenging offshore environment, which encompasses formidable conditions such as extreme temperatures, dynamic waves, and strong currents. The design and construction of offshore pipelines require robust engineering techniques and materials to ensure their integrity and functionality throughout their operational lifespan. By withstanding the harsh offshore conditions, these pipelines facilitate the efficient and secure transfer of natural gas resources from offshore locations to the onshore infrastructure or market, contributing to the overall energy supply chain [4].

Another classification considers the network configuration or layout, encompassing various types of gas pipelines based on their structural characteristics. One prominent type is the linear pipeline, which represents a straight conduit that traverses a singular direction from the source to the destination.

a)Linear pipelines constitute the most prevalent form of pipeline configuration and find widespread application across all types of gas pipeline networks. These pipelines provide a straightforward and efficient means of transporting natural gas resources, facilitating the seamless flow of gas from its origin to the intended endpoint [5].

b) A loop pipeline is a pipeline configuration characterized by its circuit-like structure, where the pipeline forms a closed loop or circuit. This type of pipeline is strategically designed to offer redundancy and ensure an uninterrupted flow of gas, particularly during disruptions or maintenance activities that may occur along the pipeline. By creating a looped pathway, the loop pipeline enables gas to be rerouted, bypassing any affected sections, thereby maintaining a continuous supply of gas to the intended destinations. This design feature enhances the reliability and resilience of the gas transportation system, mitigating the impact of potential disruptions and minimizing downtime during maintenance operations [6].

c) A lateral pipeline is a branching pipeline configuration that diverges from the main pipeline and is dedicated to serving a specific geographical area or customer. This type of pipeline is frequently employed in distribution pipeline networks, where it facilitates the delivery of natural gas to localized regions or specific end-users. By branching off from the main pipeline, the lateral pipeline enables targeted distribution, ensuring the supply of gas to distinct areas or customers with specific demands. The utilization of lateral pipelines in distribution networks optimizes the delivery process, allowing for efficient and precise allocation of natural gas resources [7].

d) A radial pipeline is a configuration in which a pipeline originates from a central point and extends outward in multiple directions to supply various areas or customers. This pipeline design is frequently employed in distribution pipeline networks, where it facilitates the efficient delivery of natural gas to multiple locations or customers from a central source. By extending radially, the pipeline ensures a reliable and direct distribution of gas to different areas or customers, allowing for effective resource allocation and optimized delivery. The implementation of radial pipelines in distribution networks enhances the overall system performance, enabling the seamless and efficient supply of natural gas to meet the specific demands of diverse end-users [8].

e) A grid pipeline refers to an intricate network of interconnected pipelines that are arranged in a grid-like pattern. This configuration is frequently employed in distribution pipeline networks, particularly in densely populated areas with a significant demand for natural gas. The grid pipeline system is designed to provide a comprehensive coverage of the target region, allowing for efficient distribution and delivery of natural gas to multiple locations within the network. By utilizing a grid-like layout, the pipeline network ensures reliable and equitable access to natural gas resources, accommodating the high demand and complex distribution requirements in densely populated areas. The grid pipeline configuration optimizes the utilization of pipeline infrastructure and enables effective management of gas supply, contributing to the seamless and uninterrupted delivery of natural gas to end-users in the designated regions [6].

Gas pipeline network optimization is a crucial and actively researched field focused on enhancing the efficiency and reliability of gas delivery to consumers. The optimization process entails a systematic approach to continually enhance the design and operation of the network, aiming to achieve optimal performance by minimizing costs and maximizing resource utilization. This includes fine-tuning various parameters such as pipeline layout, compressor placement, pressure regulation, and flow control mechanisms. The optimization objectives encompass minimizing energy consumption, reducing pressure losses, maximizing gas throughput, and optimizing the utilization of pipeline capacity. Through advanced mathematical modeling, simulation techniques, and optimization algorithms, researchers aim to identify the most effective strategies to improve the overall performance of gas pipeline networks. These optimization efforts contribute to the seamless and efficient transportation of gas, resulting in enhanced cost-effectiveness, reliability, and sustainability in the delivery of this vital energy resource to consumers [9].

The gas pipeline network is a highly complex and interconnected system consisting of a network of pipelines, compressor stations, valves, and various other components. The efficient operation of this network is of utmost importance to meet the increasing demand for gas and ensure a reliable supply to industrial, residential, and power generation sectors.

Optimizing the gas pipeline network involves addressing several challenges, including minimizing power consumption, maximizing gas flowrate, and optimizing line pack. These objectives often conflict with each other, necessitating a comprehensive approach that considers multiple factors and trade-offs. To tackle these challenges, sophisticated mathematical models are developed to accurately represent the network's behavior and capture its intricate dynamics. These models take into account factors such as pressure drop, fluid flow characteristics, line pack, and compressor power.

Simulation tools are employed to analyze the network's performance under various operating scenarios, enabling the identification of areas for improvement and the evaluation of proposed changes. By simulating different scenarios, researchers can assess the impact of modifications on the network's efficiency and reliability. This comprehensive analysis aids in making informed decisions regarding the optimization of the gas pipeline network.

Furthermore, advanced optimization algorithms are utilized to find the most effective strategies for enhancing network performance. These algorithms consider a range of constraints and objectives, such as pipeline capacity, demand fluctuations, and operational costs. By employing these algorithms, researchers can identify optimal configurations and operating conditions that minimize power consumption, maximize gas flowrate, and optimize line pack, ultimately improving the overall efficiency and effectiveness of the gas pipeline network.

By integrating advanced mathematical models, simulation tools, and optimization algorithms, researchers and industry professionals can gain valuable insights into the behavior and performance of the gas pipeline network. This knowledge enables them to make informed decisions, implement targeted improvements, and ensure a reliable and sustainable supply of gas to meet the energy demands of various sectors [10].

Optimization algorithms, such as linear programming, genetic algorithms, or metaheuristic approaches, are employed to search for the most optimal configuration and operating conditions of the network. These algorithms consider various constraints, such as pipeline capacity, demand fluctuations, and supply availability, while aiming to minimize costs and maximize overall system efficiency [11].

In this scientific field, researchers and industry professionals collaborate to develop innovative approaches, techniques, and tools to optimize gas pipeline networks. By continuously advancing our understanding and capabilities in gas pipeline network optimization, we can effectively address the evolving energy demands and contribute to the development of a more efficient and reliable gas transportation infrastructure.

The primary objective of this scientific paper is to conduct an in-depth investigation into the optimization of a gas pipeline network. This optimization process involves a complex and intricate procedure of systematically improving the network's design and operation to achieve the highest levels of efficiency and reliability in delivering gas to customers. The key focus of the optimization is to minimize the power requirements and fuel consumption of the network, while simultaneously maximizing the flowrate of gas and optimizing the line pack. By doing so, the aim is to ensure the optimal utilization of the pipeline infrastructure. To accomplish the optimization objectives, this study employs advanced mathematical models that accurately depict the behavior of the gas pipeline network. These models are designed to capture the intricate dynamics and interactions within the network. Additionally, advanced simulation tools are utilized to simulate and evaluate various operating scenarios, enabling a comprehensive analysis of the network's performance. Furthermore, state-of-the-art optimization algorithms are employed to identify the most optimal configuration and operating conditions for the network. These algorithms take into account multiple factors and constraints, aiming to strike a balance between efficiency, reliability, and cost-effectiveness. By integrating these sophisticated tools and techniques, this research endeavor strives to contribute valuable insights into the gas pipeline network optimization process. The outcomes of this study will enable industry stakeholders to make well-informed decisions and achieve enhanced performance in terms of efficiency, reliability, and cost-effectiveness. Ultimately, the findings of this research will facilitate the development of more efficient and reliable gas transportation systems, benefiting both the industry and the customers.

2. Formulation model for Gas pipeline Network

Gas pipeline network models can be developed employing a diverse range of mathematical methodologies, including optimization techniques such as linear programming (LP), nonlinear programming (NLP), mixed-integer linear programming (MILP), mixed-integer nonlinear programming (MINLP), in addition to graph theory and simulation models to replicate gas flow dynamics under diverse scenarios. The gas pipeline network formulation form involves defining the objective function, decision variables, constraints, network topology, gas properties, and input data. Subsequently, an appropriate optimization or simulation method is applied to determine the optimal solution that satisfies the requirements of the problem. The selection of the most suitable mathematical technique and optimization or simulation method relies on the specified properties of the gas pipeline network and the problem being addressed[12].

2.1.Gas properties

Gas properties are essentially for understanding and predicting the behavior of gases in different applications, including process design, combustion analysis, and gas transportation. The calculation of gas properties relies on fundamental principles of thermodynamics, fluid mechanics, and molecular theory by Smith[13].

Some of these properties that are commonly calculated for gases include.

2.1.1. Gas Density

The density and pressure of a gas as shown in the following equation form are associated by entering the compression coefficient, Z in the paradigm

$$\rho = \frac{PM}{ZRT} \tag{1}$$

Where, R is universal gas constant, M: is the gas average molecular weight and relies on its composition. Gas molecular weight is estimated by means of easy blending rule stated in the succeeding equation form in which Y_i & M_i are the mole fractions and molecular weights of sorts, respectively.

$$M = \sum M_i Y_i \tag{2}$$

2.1.2. Compressibility factor

The compression coefficient compressibility factor, Z, is utilized to change the perfect gas equation to consideration for the real gas demeanor. Conventionally, the compression coefficient is estimated by means of an equation of status, this coefficient can be uttered as a function of the characteristics of critical gas mixture, average pressure of the tube part and the temperature

$$Z = 1 + (0.257 - 0.533\frac{T_C}{T})\frac{P_{avg}}{P_C} \tag{3}$$

2.1.3. The average pseudo-critical properties of the gas mixture

The pseudo-critical temperature (Tc) and pseudo-critical pressure (Pc) of natural gas can be approximated using appropriate blending rules based on the critical properties of individual gas components.

$$T_C = \sum T_{Ci} Y_i \tag{4}$$

$$P_C = \sum P_{Ci} Y_i \tag{5}$$

2.1.4. Average pressure

The average pressure of gas can be calculated from the below formula by [14].

$$P_{avg} = \frac{2}{3}(P_1 + P_2 - \frac{P_1 * P_2}{P_1 + P_2}) \tag{6}$$

2.1.5. Specific gravity

The specific gravity of a fluid is calculated by dividing the density of the fluid by the density of a reference fluid, such as water or air, at a standard temperature.

$$S_g = \frac{density\ of\ gas}{density\ of\ air} = \frac{M_{gas}}{M_{air}} \tag{7}$$

2.1.6. Average molecular weight of gas mixture

The gas molecular weight is estimated through blending rule as

$$M_{gas} = \sum M_i Y_i \tag{8}$$

2.1.7. Low heating value

The lower heating value (LHV) of a gas, referred to as the lower calorific value or net heating value, signifies the thermal energy liberated during the complete combustion of a specific quantity or mass of the gas. In the case of a gas mixture, the LHV can be determined by taking into account the lower heating values of each individual gas component and their respective mole fractions in the mixture, as denoted by the subsequent equation: -

$$LHV = \frac{\sum y_i M_i LHV_i}{\sum y_i M_i} \tag{9}$$

2.2.Pipeline network calculations

2.2.1. Pipeline volume flowrate equation

The volume flowrate in a pipeline refers to the amount of fluid (gas or liquid) that passes through the pipeline per unit of time. It represents the volume of fluid that flows past a specific point in the pipeline over a given period. The volume flowrate of gas in pipeline depends on several factors, including the diameter of pipeline, pressure of suction and discharge, length of pipe segment, friction factor and the gas properties being transported (such as base pressure and temperature, gravity, compressibility factor). One common formula used to calculate the volume flow rate is the general equation[14]

$$Q = 77.54\left(\frac{T_b}{P_b}\right)\left(\frac{P_1^2 - P_2^2}{G*T*Le*Z*f}\right) * D^{2.5} \tag{10}$$

2.2.2. Pipeline mass flowrate equation

By quantifying the mass flowrate within a pipeline, engineers and operators are able to evaluate the mass transport phenomena, ascertain the energy demands, and monitor the efficacy and functionality of the pipeline system. Furthermore, this calculation is instrumental in the optimization of gas transportation and distribution processes. The mass flowrate can be determined using the subsequent equation:

$$\dot{m} = \frac{Q*Mwt(avg.)}{72.2} \tag{11}$$

2.2.3. Friction factor

The friction factor (f) in pipeline flow is a dimensionless quantity that characterizes the resistance to flow caused by the roughness of the pipeline surface and other factors such as turbulence and viscosity. It is an important parameter in pipeline design and operation, as it affects the pressure drop and energy losses. it can be determined using empirical equations or experimental data. The most commonly used equation for estimating the friction coefficient is the Nikuradse equation, which is an implicit equation that relates the friction factor to the roughness height of the pipeline surface (ε), and the diameter of the pipeline (D). The Nikuradse equation is given by[15].

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon/D}{3.7}\right) \tag{12}$$

2.3.Power demand reduction

In transition systems of natural gas, compressor stations consume a significant portion of energy. Thus, decrease their energy requirements can efficiently raise the competence of pipeline system and the operating revenue. In addition to, most of compressors run on gas. Efforts to reduce the energy consumption of compressor stations in gas transmission systems are of paramount importance due to their potential to decrease greenhouse gas emissions and improve environmental conditions. Compressor stations play a crucial role in the operation of natural gas pipelines as they provide the necessary energy to ensure continuous gas flow and maintain desired pressures throughout the pipeline network. The energy supplied by the compressor can be quantified as head, which represents the amount of energy supplied per unit mass of gas. The determination of the head value can be achieved through the utilization of the following equation [16].

$$H = ZRT \frac{K}{K-1} [\left(\frac{p_d}{P_S}\right)^{\frac{(K-1)}{K}} - 1] \tag{13}$$

In which K is estimated via Pambour [17]

$$K = \frac{\sum C_{pi} MY_i}{\sum C_{pi} MY_i - R} \tag{14}$$

We can estimate the energy provided to the gas in the compressor by Demissie [18].

$$Power = \frac{Q.H}{\eta_{is}} \tag{15}$$

2.4.The fuel consumption of compressor

the fuel consumption of compressors is essential for ensuring energy efficiency, reducing operational costs, and promoting sustainability in various industries that rely on compression systems, including oil and gas, petrochemicals, and power generation.

$$\dot{\boldsymbol{m}}_f = \frac{\mathbf{10^6} \boldsymbol{W}}{\eta_m \eta_d \boldsymbol{LHV}} \tag{16}$$

2.5.Line pack in pipeline

Line pack indicates to the amount of gas that is stored in a pipeline to maintain system pressure and meet fluctuations in demand. When natural gas is delivered through a pipeline system, the gas flow rate and pressure can vary depending on the demand from customers. To ensure that the system pressure remains within a safe and efficient range, pipeline operation often use line pack to store excess gas during periods of low demand and release it during periods of high demand.

Line pack is typically measured in terms of the amount of gas stored per unit length of pipeline, such as cubic feet per mile, or cubic meters per kilometer. The amount of line pack that is required depends on a variety of factors, including the size and capacity of the pipeline, the demand patterns of the customers, and the characteristics of the gas flow, such as pressure and temperature.

The value of line pack in MMscf is determined by using the following equation, Menon [8].

$$LP = 7.885x10^{-7} \left(\frac{T_{SC}}{P_{SC}}\right) \left(\frac{P_{avg}}{Z * T}\right) (D^2 * L) \tag{17}$$

2.6.Total cost

The total cost of a natural gas network is influenced by several factors, including the length and diameter of the pipelines, the required pressure and flow rate capacity, and any specific engineering requirements [19].

$$Total\ cost = operating\ cost + fixed\ cost \tag{18}$$

$$Operating\ cost = 100000 + (Power \times 850) \tag{19}$$

$$Fixed\ cost = (1495.4 \times Ln(Yr) - 11353) \times D \times 250 \times L/1600 \tag{20}$$

3. Multiple criteria decision making (MCDM)

Multiple criteria decision making (MCDM) is a decision-making framework that is used to evaluate and select alternatives based on multiple criteria or objectives. MCDM is a useful tool in situations where there are multiple and competing objectives that need to be considered when making decisions. The MCDM process involves identifying the decision problem and the available alternatives, determining the criteria or objectives that are relevant to the problem, determining the relative significant of the criteria, evaluating the alternatives based on the criteria, this can be done using various techniques, such as scoring or ranking the alternatives based on their performance on each criterion. Once the alternatives have been evaluated, the decision-maker needs to determine the trade-offs between the different criteria or objectives. This involves balancing the relative significant of each criterion against the performing of each alternative on that criterion, and finally making the decision based on the overall evaluation. MCDM has a wide range of uses in fields such as finance, engineering, environmental management, and healthcare. However, it is important to note that MCDM can be challenging due to the subjective nature of the evaluation process, the difficulty in assigning weights to criteria, and the potential for information overload. Therefore, it is important to use a rigorous and transparent decision-making process that involves multiple stakeholders and to continually review and update the criteria and weights as new information becomes available [20].

$$\varphi = \begin{array}{c} \\ \gamma_1 \\ \gamma_2 \\ \vdots \\ \vdots \\ \gamma_m \end{array} \begin{array}{c} \begin{array}{ccccc} \beta_1 & \beta_2 & .. & .. & \beta_n \end{array} \\ \begin{bmatrix} \lambda_{11} & \lambda_{12} & .. & .. & \lambda_{1n} \\ \lambda_{21} & \lambda_{22} & .. & .. & \lambda_{2n} \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ \lambda_{m1} & \lambda_{m2} & .. & .. & \lambda_{mm} \end{bmatrix} \end{array} \tag{21}$$

Where,γ_i,($i = 1,2, \dots\dots, m$) are alternative β_j,($j = 1,2 \dots\dots, n$)are criteria, for a clear view of this method.

After these endeavors, the subsequent step involves choosing a suitable approach to aid in the evaluation and prioritization or enhancement of the potential alternatives or strategies, ultimately determining the optimal choice. In this paper the optimization is carried out using VIKOR method. The VIKOR (**VI**ekriterijumsko **KO**mpromisno **R**angiranje) method is a multi-criteria decision-making technique that is used for optimization and ranking of alternatives in complex systems. It is particularly suitable for problems with conflicting criteria where a compromise solution needs to be found[21]. The compromise ranking algorithm of VIKOR involves the following steps: -

Step1:
The most common normalization method is;

1- for max, we have

$$\eta_{ij} = \frac{\lambda_{ij} - min(\lambda_{ij})}{max\ (\lambda_{ij}) - min(\lambda_{ij})} \ ,(i \in m \quad , j \in n) \tag{22}$$

2- for min, we have

$$\eta_{ij} = \frac{max(\lambda_{ij}) - \lambda_{ij}}{\max\ (\lambda_{ij}) - \min(\lambda_{ij})} \ , \ (i \in m \quad , j \in n) \tag{23}$$

As a result, a standardized decision matrix M is acquired indicating the relative performing of the substitutions as:

$$\mu = \begin{bmatrix} \eta_{11} & \eta_{12} & \cdot\cdot & \cdot\cdot & \eta_{1n} \\ \eta_{21} & \eta_{22} & \cdot\cdot & \cdot\cdot & \eta_{2n} \\ \cdot\cdot & \cdot\cdot & \cdot\cdot & \cdot\cdot & \cdot\cdot \\ \cdot\cdot & \cdot\cdot & \cdot\cdot & \cdot\cdot & \cdot\cdot \\ \eta_{m1} & \eta_{m2} & \cdot\cdot & \cdot\cdot & \eta_{mn} \end{bmatrix} \tag{24}$$

Step2:
The standard deflection method estimates the weights of purposes thru:

$$\tau_i = \frac{\sigma_i}{\sum_k^m \sigma_k}, \text{ where,} \tag{25}$$

$$\sigma_i = \sqrt{\frac{\sum_{i=1}^m (\lambda_i - \lambda^{\sim})^2}{n-1}} \tag{26}$$

And $\lambda^{\sim}$= mean variable

$$\lambda^{\sim} = \sum_{i=1}^m \lambda_i / n \tag{27}$$

Step 3

Determining the optimal γ_i^+ and the worst γ_i^- values of all criterion function, i=1, 2,………,n

$$\gamma_i^+ = max\, \gamma_{ij} \tag{29}$$

$$\gamma_i^- = min\, \gamma_{ij} \tag{30}$$

Step 4

Compute the "utility" and "feasibility" metrics for every alternative. The value representing the utility metric (α_j) represents the relative proximity of each alternative to the best value for each criterion, considering the weights assigned to each criterion. The feasibility value (ϑ_j) represents the relative distance of each alternative from the worst value for each criterion.

$$\alpha_j = \sum_{i=1}^n W_i \frac{(\gamma_i^+ - \gamma_{ij})}{(\gamma_i^+ - \gamma_i^-)} \tag{31}$$

$$\vartheta_j = max\ (W_i \frac{(\gamma_i^+ - \gamma_{ij})}{(\gamma_i^+ - \gamma_i^-)})\ , where\ \mathrm{j}=1, 2\ldots\ldots, \mathrm{m} \tag{32}$$

Step 5

The closeness coefficient (β_j) measures the compromise between the utility and feasibility values for each alternative. It is calculated using a weighted linear combination of the utility and feasibility values. The weights assigned to utility and feasibility can be adjusted based on the decision maker's preferences.

$$\boldsymbol{\beta_j = v \frac{(\alpha_j - \alpha^+)}{(\alpha^- - \alpha^+)} + (1 - v) \frac{(\vartheta_j - \vartheta^+)}{(\vartheta^- - \vartheta^+)}} \tag{33}$$

Where

$$\alpha^+ = min\alpha_j \tag{34}$$

$$\alpha^- = max\alpha_j \tag{35}$$

$$\vartheta^+ = \mathrm{min}\vartheta_{\mathrm{j}} \tag{36}$$

$$\vartheta^- = \mathrm{max}\vartheta_{\mathrm{j}} \tag{37}$$

The parameter *v*, which signifies the weight assigned to the strategy or maximum group utility of most criteria, is introduced, and set as $v = 0.5$.

Step 6

Rank the alternatives based on their closeness coefficient. The alternative with the lowest value of $\boldsymbol{\beta}_{\mathbf{j}}$ is considered the best compromise solution or the optimal alternative.

4. Case Studies

4.1. Case 1 (tree)

The gas pipeline network under investigation adopts a tree-topology configuration, comprising of two compressor stations featuring a parallel arrangement of six compressors each. Within this network, a gas source is responsible for supplying natural gas to three distinct customer types located at the extremities of the network branches. The fundamental parameters outlining this configuration can be found in Figure 1. The internal diameter of all pipes is 24 inches, and the friction factor is set to 0.009. The base temperature and pressure conditions are specified as 520°R and 14.5 psia, respectively. The compressors are arranged in two pairs, namely (S1, S2) and (S4,S5), with each compressor station consisting of six centrifugal units operating in parallel. The physical properties of the gas mixture used in the network can be found in Table 1[22].

Table 1. Physical Properties of gas mixture for Case 1

Gas component	**C1**	**C2**	**C3**
Mole Fraction Yi	0.700	0.250	0.050
Molecular mass($\mathbf{gmole^{-1}}$)	16.0400	30.0700	44.1000
Lower heating value at 15°C and 1 bar ($\mathbf{MJm^{-3}}$)	37.7060	66.0670	93.9360
Critical pressure (bar)	46.0000	48.8000	42.5000
Critical temperature (K)	190.600	305.400	369.800
Heat capacity at constant pressure ($\boldsymbol{J.mol^{-1}.K}$)	35.6635	52.8480	74.9160

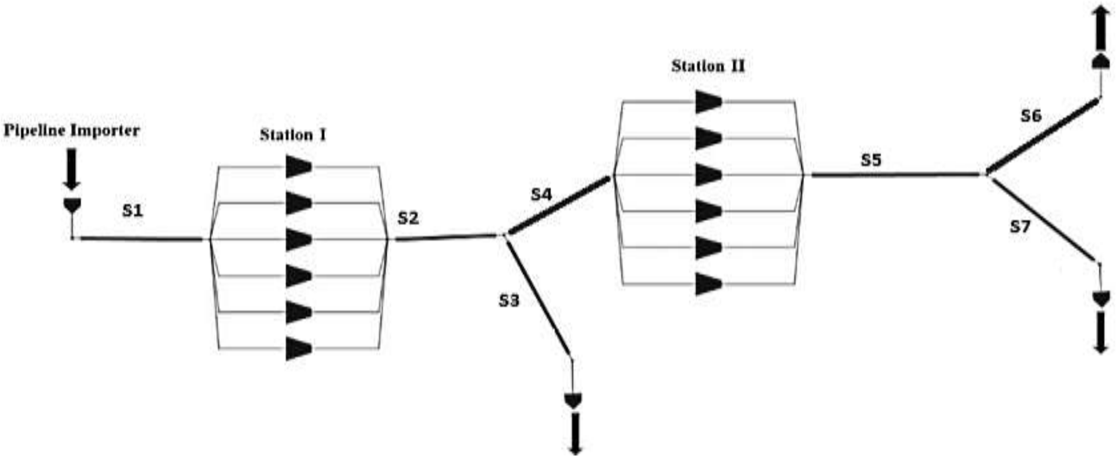

Figure 1. Pipeline network for Case 1.

Table 2 displays data specifications for different scenarios including flowrate, power, line pack and fuel consumption for case 1.

Table 2. Data Specifications for Case 1.

Scenario	**Pmin (psi)**	**Pmax (psi)**	**Flowrate (MMscf)**	**Power (hp)**	**Line pack (MMscf)**	**Fuel consumption (klb/sec)**
1	653	1016	261.41	5,720	104.244	277.064
2	700	1000	262.44	5,046	106.839	244.449
3	750	950	234.35	4,010	111.070	194.240
4	800	1000	321.57	4,103	118.460	198.736
5	850	1000	284.44	2,506	122.718	121.395

The normalized decision matrix results by using equation (22-23) are shown in Table 3.

Table 3. The normalized decision matrix Case1.

Scenario	**Flowrate**	**Power**	**Line pack**	**Fuel consumption**
1	0.31031	0.00000	0.00000	0.00000
2	0.32210	0.20951	0.14044	0.20951
3	0.00000	0.53205	0.36946	0.53205
4	1.00000	0.50317	0.76941	0.50317
5	0.57436	1.00000	1.00000	1.00000

By using VIKOR method which presented previously, the results of calculation of the standard deviation ($\boldsymbol{\sigma_i}$) and the objective weight ($\boldsymbol{\tau_i}$) using equation (25-26) are presented in Table 4.

Table 4. Standard deviation ($\boldsymbol{\sigma_i}$) and objective weight ($\boldsymbol{\tau_i}$) results Case 1.

Standard Deviation ($\boldsymbol{\sigma_i}$)	0.37281	0.37828	0.42106	0.37828
Objective weight ($\boldsymbol{\tau_i}$)	0.24046	0.24398	0.27157	0.24398

The next step is calculating the $\boldsymbol{\mu}$ matrix. The results are presented in Table 5 for each scenario.

Table 5. The normalized decision matrix Case 1.

Scenario	**Flowrate**	**Power**	**Line pack**	**Fuel consumption**
1	0.16584	0.24398	0.27157	0.24398
2	0.16301	0.19287	0.23344	0.19287
3	0.24046	0.11417	0.17124	0.11417
4	0.00000	0.12122	0.06262	0.12122
5	0.10235	0.00000	0.00000	0.00000

The results of utility $\boldsymbol{\alpha_j}$, feasibility $\boldsymbol{\vartheta_j}$, and closeness coefficient $\boldsymbol{\beta_j}$ are presented in Table 6 for each scenario.

Table 6. Results obtained by VIKOR method Case 1.

Scenario	**Utility ($\boldsymbol{\alpha_j}$)**	**Feasibility ($\boldsymbol{\vartheta_j}$)**	**Closeness coefficient ($\boldsymbol{\beta_j}$)**
1	0.92538	0.27157	1.00000
2	0.78217	0.23344	0.80031
3	0.64004	0.24046	0.73471
4	0.30506	0.12122	0.17890
5	0.10235	0.10235	**0.08461**

The optimal configuration is observed in the fifth scenario, characterized by a pressure range of 580 -1000 pounds per square inch (psi), a flow rate of 284.44 million standard cubic feet per day (MMscfd), compressor power consumption of 2,506 horsepower (hp), a line pack of 122.718 million standard cubic feet (MMscf), and fuel consumption of 121.395 thousand pounds per second (klb/sec).

The calculation of total cost is a critical aspect in the optimization of gas pipeline networks. Accurate assessment of this factor plays a crucial role in decision-making processes related to network design and operation. By determining the total cost, valuable insight can be gained, enabling stakeholders to make informed decisions regarding network configuration, resource allocation, and cost-effective operation. Total cost is calculated for each scenario using equations 18-20 and results are shown below through Table 7.

Table 7. Total fuel consumption for each scenario Case 1.

Scenario	Total cost (M$/Yr)
1	8.52
2	7.95
3	7.07
4	7.15
5	**5.79**

The minimum total cost observed in the study was determined to be **5.79** million dollars per year. This optimal result was obtained in the fifth scenario, which corresponds to the optimal outcome identified using the VIKOR method.

4.2.Case 2 (branched-cyclic)

The second case study, which pertains to network characteristics, was sourced from the real-world data provided by the French Company GdF Suez. The presented transmission network is depicted in Figure 2 in a schematic manner, reflecting its multisupply and multidelivery nature. This case study exhibits a more intricate combinatorial aspect compared to case study 1 due to the presence of three loops and seven compressor stations.The transmission network comprises a total of 19 delivery points, denoted by small empty circles, from which gas is extracted. Gas supply can be obtained from six different points, represented by hexagons. Additionally, the network considers 20 intermediate nodes that facilitate interconnections and, in certain instances, explicitly specify modifications in design parameters. Overall, the network encompasses a total of 45 nodes and 30 pipe arcs. Furthermore, there are seven compressors strategically positioned throughout the network to compensate for pressure losses. The base temperature and pressure conditions are specified as 520°R and 14.5 psia, respectively. The length, inside diameter, and roughness of each pipe are shown in Table 8 [23].

Table 8. Length and inside diameter data for Case 2

Arc	O.D (in)	L (mile)	Roughness (m)	Arc	O.D (in)	L (mile)	Roughness (m)
G1(26:25)	30	40.06	0.00002	G16(10-11)	30	59.81	0.00001
G2(25-24)	28	63.50	0.00002	G17(12-13)	30	74.82	0.00001
G3(23-22)	28	50.25	0.00001	G18(45-44)	36	3.06	0.00001
G4(22-21)	26	16.94	0.00001	G19(44-43)	48	19.31	0.00001
G5(39-38)	48	107.94	0.00001	G20(43-19)	36	33.38	0.00001
G6(30-29)	48	3.06	0.00001	G21(18-17)	36	34.06	0.00001
G7(28-36)	48	76.38	0.00001	G22(17-14)	36	48.13	0.00001
G8(37-40)	36	50.81	0.00001	G23(15-16)	32	55.63	0.00001
G9(36-41)	48	26.00	0.00001	G24(7-6)	20	39.94	0.00002
G10(41-42)	42	17.75	0.00001	G25(26-25)	42	40.06	0.00001
G11(1-2)	36	13.50	0.00001	G26(27-31)	42	127.81	0.00001
G12(2-3)	42	8.88	0.00001	G27(31-32)	42	22.63	0.00001
G13(3-5)	42	27.06	0.00001	G28(33-34)	36	78.63	0.00001
G14(4-3)	24	29.25	0.00001	G29(34-35)	36	42.31	0.00001
G15(8-9)	24	17.44	0.00001	G30(20-19)	42	0.0006	0.00001

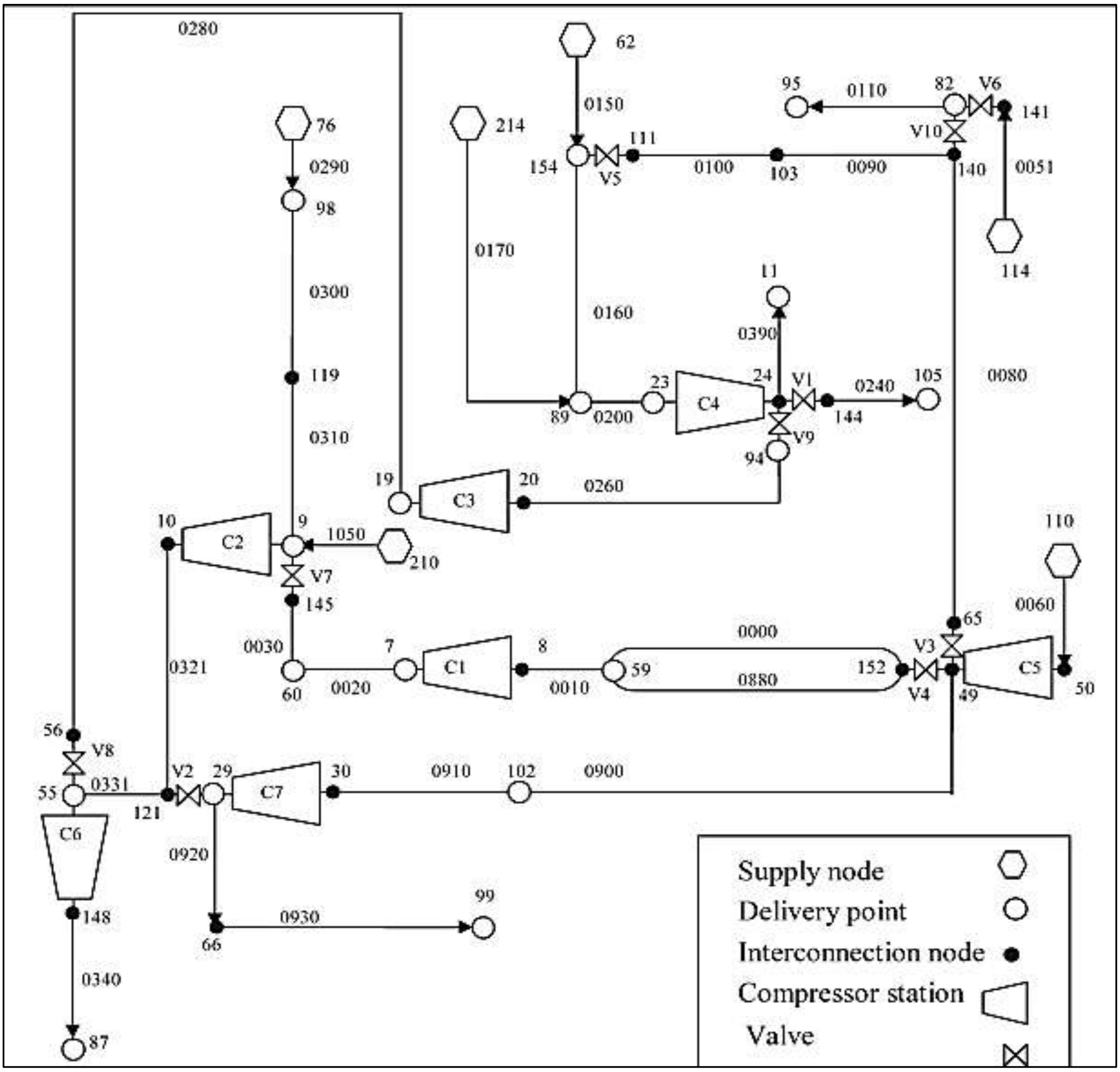

Figure 2. Pipeline network for Case 2.

Table 9 displays data specifications for different scenarios including flowrate, power, and line pack for case 2.

Table 9. Data Specifications for Case 2.

Scenario	Pmin (psi)	Pmax (psi)	Flowrate (MMscf)	Power (hp)	Line pack (MMscf)	Fuel consumption (klb/sec)
1	668	1089	216510.8	7,916	11608	766.78
2	668	1147	66563.84	4,158	12681	402.78
3	668	1176	67718.16	3,465	13123	167.80
4	675	1118	65397.79	3,525	12219	341.44
5	668	1060	162506.2	6,897	11348	668.12

The normalized decision matrix results by using equation (22-23) are shown in Table 10.

Table 10. The normalized decision matrix Case2.

Scenario	Flowrate	Power	Line pack	Fuel consumption
1	1.00000	0.00000	0.14649	0.00000
2	0.00772	0.84421	0.75122	0.60770
3	0.01536	1.00000	1.00000	1.00000
4	0.00000	0.98648	0.49080	0.71012
5	0.64262	0.22883	0.00000	0.16472

By using VIKOR method which presented previously, the results of calculation of the standard deviation (σ_i) and the objective weight(τ_i) using equation (25-26) are presented in Table 11.

Table 11. Standard deviation (σ_i) and objective weight (τ_i) results Case 2.

Standard Deviation (σ_i)	0.46324	0.46531	0.41403	0.40869
Objective weight (τ_i)	0.26452	0.26570	0.23642	0.23337

The next step is calculating the μ matrix. The results are presented in Table 12 for each scenario.

Table 12. The normalized decision matrix Case 2.

Scenario	Flowrate	Power	Line pack	Fuel consumption
1	0.00000	0.26570	0.20178	0.23337
2	0.26247	0.04139	0.05882	0.09155
3	0.26045	0.00000	0.00000	0.00000
4	0.26452	0.00359	0.12038	0.06765
5	0.09453	0.20490	0.23642	0.19493

The results of utility α_j, feasibility ϑ_j, and closeness coefficient β_j are presented in Table 13 for eachscenario.

Table 13. Results obtained by VIKOR method Case 2.

Scenario	Utility (α_j)	Feasibility (ϑ_j)	Closeness coefficient (β_j)
1	0.70085	0.26570	0.96819
2	0.45423	0.26247	0.65090
3	0.26045	0.26045	**0.41040**
4	0.45614	0.26451	0.68778
5	0.73078	0.23641	0.51464

The optimal configuration is observed in the third scenario, characterized by a pressure range of 668 -1176 (psi), a flow rate of 67718.16 (MMscfd), compressor power consumption of

3,465 (hp), a line pack of 13123 (MMscf), and fuel consumption of 167.80 (klb/sec).

The calculation of total cost is a critical aspect in the optimization of gas pipeline networks. Accurate assessment of this factor plays a crucial role in decision-making processes related to network design and operation. By determining the total cost, valuable insight can be gained, enabling stakeholders to make informed decisions regarding network configuration, resource allocation, and cost-effective operation. Total cost is calculated for each scenario using equations 18-20 and results are shown below through Table 14.

Table 14. Total fuel consumption for each scenario Case 2.

Scenario	Total cost (M$/Yr)
1	15.43
2	12.24
3	**11.65**
4	12.51
5	14.57

The minimum total cost observed in the study was determined to be 11.65 million dollars per year. This optimal result was obtained in the third scenario, which corresponds to the optimal outcome identified using the VIKOR method.

CONCLUSION

This study presents a novel approach for optimizing natural gas transmission networks, taking into account the operational considerations of pipelines through a multi-criteria decision-making process. The proposed model aims to address the simultaneous optimization of four conflicting objectives: maximizing the delivery flow rate, minimizing power consumption, minimizing fuel consumption, and maximizing line pack. To validate the effectiveness of the model, it was applied to two distinct network cases, and the VIKOR method was utilized to determine the optimal scenario. Through this analysis, important insights were obtained concerning the total cost and fuel consumption, providing valuable information for decision-making processes. The proposed multi-objective optimization approach can be extended to tackle other gas pipeline network optimization problems that involve conflicting objectives. Additionally, combining this approach with conventional techniques has the potential to further enhance the optimization process. Future research in this field could explore alternative optimization techniques and consider additional factors such as environmental impact and safety. Furthermore, it is crucial to examine the scalability of the proposed approach to ensure its effectiveness in larger and more complex gas transmission networks. By continuing to advance the understanding and application of this optimization approach, significant advancements can be made in optimizing gas pipeline networks, leading to improved efficiency, cost-effectiveness, and overall performance in the transportation of natural gas.

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Nomenclature

Q	is volumetric flow rate in MMSCFD
Pb	is base pressure in psia
Tb	is base temperature in °R
P1	is upstream pressure in psia
P2	is downstream pressure in psia
Tf	is gas flowing temperature in °R
G	is gas gravity, dimensionless
ρ_g	is gas density in lb/ft^3
ρ_{air}	is air density in lb/ft^3
Z	is gas compressibility factor
D	is pipe inside diameter in inch
L	is equivalent length in mile
$\dot{m}$	is gas flowrate in lb/s
Mwt(avg.)	is average molecular weight of gas
mole%(i)	is the mole percent of each component in gas
Mwt(i)	is the molecular weight of each component in gas
T_{PC}	is the pseudo critical temperature °R
y_i	is the mole fraction of each component
P_{PC}	is the pseudo critical pressure psi
Pavg.	is average pressure in psi
T	is gas temperature in K
Tc	is the critical temperature in k
Pc	is the critical pressure in Psi
K	is specific heat ratio (Cp/Cv) assume it to be 1.26
T1	is suction temperature in °R
W	is rate of power in hp
Vb	is line pack in pipe segment in MMSCFD
P	station horsepower
$\dot{m}_f$	Is the mass flowrate of consumed gas as fuel for the compressor in lb/s.
P_w	Is the power required for compression process in kw
η_m	Is the mechanical efficiency of compressor it is ranging between 0.8-0.9 (taking=0.9)
η_d	Is the driver efficiency of compressor its value up to 0.5 for centrifugal compressor (taking=0.35)
LHV	Is the lower heating value of gas mixture in kj/kg.
y_i	Is mole fraction of percent of gas component i, dimensionless.
M_i	Is molecular weight of gas component I, in g/mol.
LHV_i	The mass low heating value of molecules composing the gas in kj/kg.
MMSCFD	Million standard cubic feet per day

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