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ENHANCING GAS PIPELINE NETWORK EFFICIENCY THROUGH VIKOR METHOD

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Abstract: *The optimization of gas pipeline networks is critical for efficient and cost-effective transportation of natural gas. This study develops a mathematical model capable of analyzing different network configurations, including branched and branched-cyclic topologies, to explore the optimization of a gas pipeline network conditions. The research provides valuable insights into the gas pipeline network optimization process, empowering industry stakeholders to make informed decisions and enhance performance in terms of efficiency, reliability, and cost-effectiveness. To attain these objectives, this study utilizes advanced simulation tools, state-of-the-art optimization algorithms, and sophisticated mathematical models that accurately represent the network's behavior. The optimization process aims to minimize the network's power requirements while simultaneously maximizing gas flowrate and optimizing line pack, ensuring optimal utilization of the pipeline infrastructure. The VIKOR (VIekriterijumsko KOmpromisno Rangiranje) method is identifying the most optimal network configuration and operating conditions. Our analysis applies this approach to three case studies, demonstrating its effectiveness in identifying the best network configurations. Additionally, the calculations of total cost and fuel consumption coincide with relative closeness which confirm on accuracy of our proposed method whereas optimal scenarios of the three cases have the minimum total cost among all scenarios. In conclusion, this research successfully develops a mathematical model and optimization approach to tackle the complexities of gas pipeline network optimization. The application of The VIKOR method and the analysis of case studies offer substantial evidence of its effectiveness.*

Key words: *Gas pipeline optimization, multi-criteria decision making, branched and branched-cyclic topologies, Line pack optimization, Energy consumption, VIKOR method.*

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1. Introduction

The transportation of natural gas through pipelines is a critical component of the energy infrastructure for many countries worldwide. The growing demand for natural gas as a more environmentally friendly substitute for conventional fossil fuels has resulted in many countries investing in expanding their gas pipeline networks (F. Li et al., 2023)

Optimizing gas pipeline networks is vital to enhance their performance and efficiency, and different types of networks can be classified based on usage and configuration. One classification considers the network uses: a) long-distance transmission pipelines that transport natural gas from production sites to large urban areas, industrial centers, and power plants. These pipelines can span hundreds or even thousands of kilometers, and they are typically designed to operate at high pressures to minimize energy loss during transportation (Zou et al., 2016). b) Distribution pipelines are responsible for transporting natural gas to customers in residential, commercial, and small industrial sectors. These pipelines exhibit comparatively smaller dimensions and operate at lower pressure levels in comparison to their transmission counterparts. They typically supply gas to local distribution companies or utilities, which then distribute it to end-users through a network of local distribution lines (Vetter et al., 2019). c) Gathering pipelines serve the purpose of collecting natural gas from multiple production wells and facilitating its transportation to processing plants or transmission pipelines. These pipelines are predominantly situated in rural regions and operate at pressure levels lower than those observed in transmission or distribution pipelines (Guo & Ghalambor, 2014). d) Offshore pipelines transport natural gas from offshore production sites to onshore facilities or directly to market. These pipelines are designed to withstand the harsh offshore environment, including extreme temperatures, waves, and currents (Guo et al., 2013)

However, addressing various challenges, such as minimizing power consumption, maximizing gas flow rate, and optimizing line pack, requires a comprehensive approach that considers multiple factors and trade-offs.

Advanced mathematical models, simulation tools, and optimization algorithms are developed to optimize gas pipeline networks. In this scientific field, researchers and industry professionals collaborate to develop innovative approaches, techniques, and tools to optimize gas pipeline networks continuously.

This paper aims to optimize a gas pipeline network through the utilization of an advanced mathematical model, sophisticated simulation tools, and state-of-the-art optimization algorithms. The optimization process's goal is to simultaneously minimize the network's power requirements, maximize gas flow rate, and optimize line pack, ensuring efficient use of the pipeline infrastructure.

The VIKOR method is widely favored for its adeptness in producing compromise solutions that harmonize diverse criteria and objectives. It revolves around the concept of "proximity to the ideal solution," aiming to identify a solution that closely aligns with the ideal while also minimizing its deviation from the least favorable alternative. In addressing such challenges, MCDM methods are often employed. However, due to the plethora of available methods and the array of computational algorithms within them, selecting the most suitable approach for a given decision-making scenario becomes intricate. This in turn renders the method selection itself a challenge of the MCDM realm (Brodny & Tutak, 2023).

This paper employs the robust VIKOR method, a potent multi-criteria decision-making technique, to identify the optimal network configuration and operational conditions. It was initially introduced by (Opricovic & Tzeng, 2004). The study also conducts an analysis to determine the total cost and fuel consumption, providing valuable insights for decision-making. By incorporating the VIKOR method with Standard Deviation ($\boldsymbol{\sigma_i}$) weighting (Paradowski et al., 2021), the research determines and justify criteria weights for delivery flow rate, power consumption, and line pack based on their relative importance in gas transmission network optimization. Delivery flow rate was considered the most important criterion as it directly affects the ability of the network to meet demand, while power consumption and line pack were considered equally important in minimizing energy consumption and ensuring network stability, respectively

In the context of this paper, the VIKOR method is chosen for its ability to comprehensively evaluate the gas pipeline network's performance while navigating through multifaceted criteria and trade-offs.

The MCDM method, VIKOR, exhibits several favorable attributes, such as: a) Simplicity: VIKOR is characterized by its straightforward comprehension and straightforward implementation, necessitating only fundamental mathematical computations. b) Flexibility: The method adeptly handles a substantial number of criteria and alternatives, thus rendering it suitable for intricate decision-making quandaries. c) Compromise Solutions Consideration: Distinct from certain other MCDM methods, VIKOR accommodates compromise solutions. This unique feature empowers decision-makers to harmonize competing objectives, yielding resolutions amenable to all stakeholders. d) Alternative Ranking: VIKOR efficiently furnishes an alternative ranking based on their proximity to the ideal solution, furnishing decision-makers with an efficient framework for evaluation and comparison.

Nevertheless, there exist certain limitations affiliated with the employment of the VIKOR method, encompassing: a) Sensitivity to Input Data: The VIKOR method's performance can be notably influenced by variations in input data. Even minute alterations in data can yield considerably disparate rankings of alternatives. b) Unaddressed Uncertainty: Notably, the method does not explicitly grapple with the presence of uncertainty within input data. This aspect can pose a substantial constraint when confronting decision-making challenges characterized by elevated degrees of uncertainty.

The VIKOR method is a widely recognized technique employed in (MCDM) and had extensive applications in various domains, including operations (H. Li et al., 2020), supply chain management (Yang et al., 2022), and environmental management (C.-N. Wang et al., 2021). The VIKOR method has been applied in diverse fields and problem domains, such as sustainable energy development in Central and Eastern European countries (Brodny & Tutak, 2021), material selection (Jahan et al., 2011), stochastic data and subjective judgments in the extended VIKOR method (Tavana et al., 2016), and risk evaluation of construction projects using the picture fuzzy normalized projection-based VIKOR method(L. Wang et al., 2018).

In parallel, various other MCDM models, including the Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), and Grey Relational Analysis (GRA), have been applied in the context of gas pipeline network optimization. These models contribute to the ongoing efforts aimed at enhancing decision-making processes within the field of optimizing gas pipeline networks. The current state of research on gas pipeline operations lacks comprehensive strategies for effectively implementing optimization techniques to achieve maximum profitability.

To address this gap, our paper proposes a novel mechanism utilizing the MCDM (VIKOR) method to optimize pipeline activities and enhance profitability. Instead of delving extensively into numerical methods, our focus lies on providing an overview of the VIKOR method to tackle various critical pipeline optimization challenges. Our aim is to offer a clear understanding of this technique, which have demonstrated its effectiveness in improving the performance of gas pipeline systems.

2. Literature review

A recent study by R. Wang et al. (2021) proposed a new MCDM model based on the combination of fuzzy logic and the ELECTRE method for gas pipeline network optimization (R. Wang et al., 2021). Another recent study by Zhang, Li, and Zhu (2021) conducted a valuable research study that introduces a dynamic decision-making model based on the Analytic Hierarchy Process (AHP) for the planning of gas pipeline networks under uncertain demand conditions (L. Li et al., 2021).

(Ali et al., 2021) conducted a comparative analysis of the feasibility of the IPI and TAPI projects, considering various objectives. Their study aimed to identify critical activities and optimize material and transportation costs specifically for the TAPI pipeline project. To achieve these goals, the researchers utilized fuzzy TOPSIS, Fuzzy Critical Path Method (CPM), and Genetic Algorithm methodologies. The research paper is organized into several subsections, each elucidating the applications of these methods (X. Wu et al., 2018). Table 1 provides information on studies related to pipeline optimization and the level of satisfaction with municipal and public services.

Table 1. Studies related to pipeline optimization.

Author	Method	Objective function
(Manojlović et al., 1994)	Hardy Cross method and diameter correction procedure	Simulate and enhance the operation of a natural gas transport system by iteratively adjusting network parameters.
(S. Wu et al., 2000)	Mathematical model of the fuel cost minimization problem	Relaxing the fuel cost objective function and relaxing the non convex nonlinear compressor domain.
(Ríos-Mercado et al., 2002)	Reduction Technique	Minimization of fuel costs and considering the sum of fuel costs across all compressor stations.
(Y. Wu et al., 2007)	GOP primal-relaxed dual decomposition method	Reducing the cost of pipelines in a decentralized non-linear gas network, achieved by optimizing the gas flow under steady-state assumptions.
(Tabkhi et al., 2009)	the standard branch and bound solver in GAMS	Study focuses on optimizing pipeline design parameters and compressor station characteristics to meet customer requirements.
(Habibvand & Behbahani, 2012)	Genetic Algorithm	Fuel Consumption Optimization

(Üster & Dilaveroğlu, 2014)	state-of-the-art solution methodologies	Optimize the gas transmission network, including expansion or modification of an existing network, while minimizing both total investment and operational costs.
(Hu et al., 2016)	Elitist Non-dominated Sorting Genetic Algorithm II (NSGA-II)	Reducing both the investment cost and production cost of the CGEN, Addressing the combined optimal power and natural gas load flow problem, and obtain the Pareto front of the proposed multi-objective model.
(Arya & Honwad, 2018)	ant colony approach	Minimize fuel consumption in compressors while maximizing the throughput of the gas pipeline network.
(Osiadacz & Isoli, 2020)	bi-criteria approach	Reducing the operating costs of compressors and enhance the capacity of the gas network.
(Jiao et al., 2021)	Decoupled Implicit Method for Efficient Network Simulation (DIMENS) method and NS-saDE algorithm	Reducing operational costs
(J. Zhou et al., 2021)	ε-constraint method	Optimizing and maximize the delivery flow rate in a specified GDN while minimizing the cost of compressor station power consumption.
(Wen et al., 2022)	integrated optimization method	Assess the gas storage facility's maximum regulation capacity, analyze the impact of pipeline transmission and construction costs on the construction plan, and promote eco-friendly production practices for enhanced operations.

3. Methodology

Like the TOPSIS approach, VIKOR aims to select the most favorable alternative from a set of available options by determining the closest one to the Ideal Positive Solution and the farthest from the Ideal Negative Solution. The VIKOR method utilizes a vector approach to calculate compromise rankings, considering both the best and worst performance of each alternative. Figure 1 depicts the typical stages involved in the VIKOR approach that are adopted in this study.

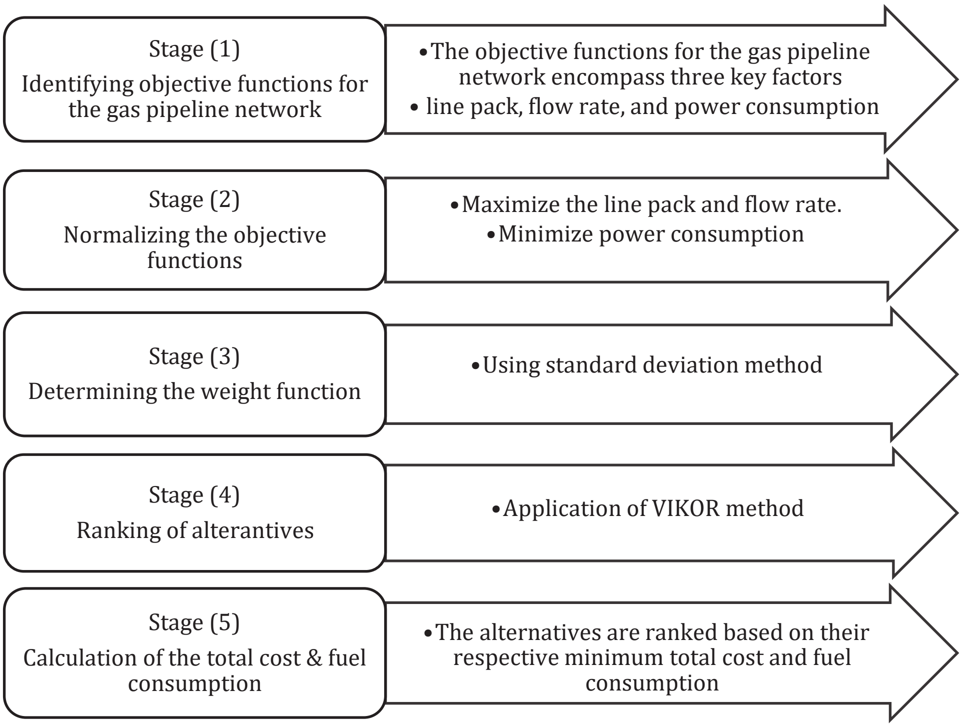

Figure 1. Flow chart of typical steps involved in the VIKOR approach.

The subsequent stages are used for optimizing and ranking of alternatives in complex systems. It is particularly suitable for problems with conflicting criteria where a compromise solution needs to be found.

3.1. Stage 1: Objective functions identification

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(X. Wu et al., 2018).

3.1.1. 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 (Menon, 2005). Some of these properties that are calculated for gases are exhibited in Appendix A.

3.1.2. Pipeline network calculations

3.1.2.1. Pipeline volume flowrate equation

The volume flowrate in a pipeline is the quantity of fluid (gas or liquid) that moves through the pipeline within a specified time frame. Calculating the volume flowrate often involves using a general equation (Coelho & Pinho, 2007).

$$Q = 77.54\left(\frac{T_b}{P_b}\right)\left(\frac{P_1^2-P_2^2}{G*T*Le*Z*f}\right)*D^{2.5} \tag{1}$$

3.1.2.2. Power demand reduction

Compressor stations in natural gas transmission consume significant energy. Reducing their energy demands can enhance pipeline efficiency and operating revenue. The energy supplied by compressors is measured as head per unit mass of gas, calculated using a specific equation (Kashani & Molaei, 2014).

$$H = ZRT\frac{K}{K-1}\left[\left(\frac{p_d}{p_S}\right)^{\frac{(K-1)}{K}} - 1\right] \tag{2}$$

In which K is estimated via Pambour (Pambour et al., 2016)

$$K = \frac{\sum C_{pi}MY_i}{\sum C_{pi}MY_i - R} \tag{3}$$

We can estimate the energy provided to the gas in the compressor by Demissie (Demissie et al., 2017).

$$\text{Power} = \frac{Q.H}{\eta_{is}} \tag{4}$$

3.1.2.3. Line pack in pipeline

Line pack in a pipeline stores gas to manage pressure and demand fluctuations. Operators store excess gas during low-demand periods and release it during high-demand times. Line pack is measured as gas stored per unit length of pipeline and depends on pipeline size, capacity, customer demand, and gas flow characteristics. Its value in MMscf is calculated using the following equation (Menon, 2005).

$$LP = 7.885x10^{-7}\left(\frac{T_{SC}}{P_{SC}}\right)\left(\frac{P_{avg}}{Z*T}\right)(D^2 * L) \tag{5}$$

3.2. Stage 2: Objective functions Normalization

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.

$$\varphi = \begin{array}{c} \\ \gamma_1 \\ \gamma_2 \\ \vdots \\ \\ \gamma_m \end{array} \begin{array}{c} \begin{array}{ccccc} \beta_1 & \beta_2 & .. & .. & \beta_n \end{array} \\ \begin{bmatrix} \lambda_{11} & \lambda_{12} & .. & .. & \lambda_{1n} \\ \lambda_{21} & \lambda_{22} & .. & .. & \lambda_{2n} \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ \lambda_{m1} & \lambda_{m2} & .. & .. & \lambda_{mm} \end{bmatrix} \end{array} \tag{6}$$

Where, γ_i,$(i = 1,2, \dots \dots, m)$ are alternative β_j ,$(j = 1,2 \dots \dots, n)$ are criteria.

The most common normalization method is:

(i) for max, we have

$$\eta_{ij} = \frac{\lambda_{ij}-min(\lambda_{ij})}{max\,(\lambda_{ij})-min(\lambda_{ij})} \text{ ,}(i\epsilon m \quad , \; j\epsilon n) \tag{7}$$

(ii) for min, we have

$$\eta_{ij} = \frac{max(\lambda_{ij})-\lambda_{ij}}{\max(\lambda_{ij})-\min(\lambda_{ij})}, \ (i\epsilon m \quad , \ j\epsilon n) \tag{8}$$

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

$$\mu = \begin{bmatrix} \eta_{11} & \eta_{12} & .. & .. & \eta_{1n} \\ \eta_{21} & \eta_{22} & .. & .. & \eta_{2n} \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ \eta_{m1} & \eta_{m2} & .. & .. & \eta_{mn} \end{bmatrix} \tag{9}$$

3.3. Stage 3: Weight function Determination

(i) The standard deflection method estimates the weights of purposes thru:

$$\tau_i = \frac{\sigma_i}{\sum_k^m \sigma_k}, \text{ where,} \tag{10}$$

$$\sigma_i = \sqrt{\frac{\sum_{i=1}^m (\lambda_i - \lambda^\sim)^2}{n-1}} \tag{11}$$

And $\lambda^\sim$= mean variable

$$\lambda^\sim = \sum_{i=1}^m \lambda_i / n \tag{12}$$

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

$$\gamma_i^+ = max\,\gamma_{ij} \tag{13}$$

$$\gamma_i^- = min\,\gamma_{ij} \tag{14}$$

(iii) 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.

$$\alpha_j = \sum_{i=1}^n W_i \frac{(\gamma_i^+ - \gamma_{ij})}{(\gamma_i^+ - \gamma_i^-)} \tag{15}$$

$$\vartheta_j = max \left[W_i \frac{(\gamma_i^+ - \gamma_{ij})}{(\gamma_i^+ - \gamma_i^-)} \right], where \text{j=1, 2……., m} \tag{16}$$

(iv) 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. 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.

$$\beta_j = \left[v \frac{(\alpha_j - \alpha^+)}{(\alpha^- - \alpha^+)} + (1-v) \frac{(\vartheta_j - \vartheta^+)}{(\vartheta^- - \vartheta^+)} \right] \tag{17}$$

Where,

$$\alpha^+ = min\alpha_j \tag{18}$$

$$\alpha^- = max\alpha_j \tag{19}$$

$$\vartheta^{+} = min\vartheta_{j} \tag{20}$$

$$\vartheta^{-} = \max\vartheta_{j} \tag{21}$$

3.4. Stage 4: Ranking of alternatives

Rank alternatives based on closeness coefficient. The alternative with the lowest (β_j) is the best compromise solution or optimal choice.

3.5. Stage 5: Total cost & fuel consumption Calculation

3.5.1. Total cost

Total cost of a natural gas network depends on several parameters as in the following equations(Edgar et al., 2001).

$$Total\ cost = Operating\ cost + Fixedcost \tag{22}$$

$$Operating\ cost = 100000 + (Power \times 850) \tag{23}$$

$$Fixed\ cost = (1495.4 \times Ln(Yr) - 11353) \times D \times 250 \times L/1600 \tag{24}$$

3.5.2. The fuel consumption of compressor

Compressor fuel consumption is vital for energy efficiency, cost reduction, and sustainability in various industries with compression systems, like oil and gas, petrochemicals, and power generation.

$$\dot{m}_f = \frac{10^6 W}{\eta_m \eta_d LHV} \tag{25}$$

4. Illustrative Case Studies

4.5. Case 1: Tree

The gas pipeline network under consideration is composed of ten nodes connected by six arcs: (2-3), (4-5), (5-6), (5-7), (8-9), and (9-10). Each pipe within the network has a length of 50 miles. The internal diameter of all pipes is specified as NPS 36 with a wall thickness of 0.375 inches, and a friction factor of 0.0090 is utilized. The base temperature and pressure conditions for the network are set at 520°R and 14.5 psia, respectively (S. Wu et al., 2000). The compressor stations, denoted as {(1,2), (3,4), (3,8)}, are equipped with five centrifugal units operating in parallel. The physical properties of the gas mixture utilized within the network can be found in Table 2. The pipeline network can be observed in Figure 2.

Table 2. Physical Properties of gas mixture for Case 1

Gas component	C1	C2	C3
Mole Fraction Yi	0.700	0.250	0.050
Molecular mass($gmole^{-1}$)	16.0400	30.0700	44.1000
Lower heating value at 15°C and 1 bar (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 ($J.mol^{-1}.K$)	35.6635	52.8480	74.9160

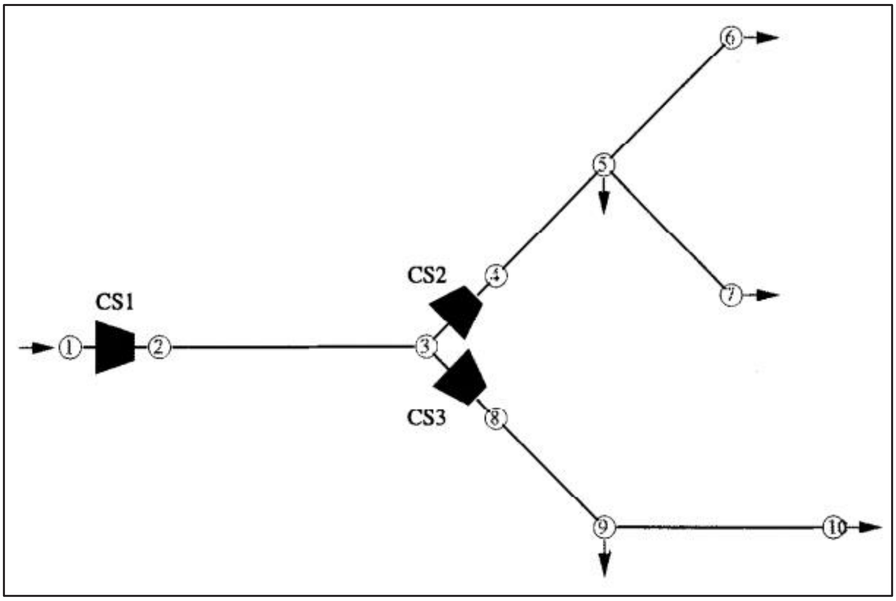

Figure 2. Pipeline network for Case 1.

Table 3 displays data specifications for different scenarios including flowrate, power, and line pack for case 1.

Table 3. Data Specifications for Case 1.

Scenario	Pmin (psi)	Pmax (psi)	Flowrate (MMscf)	Power (hp)	Line pack (MMscf)
1	600	800	645.432	5,350	140.640
2	650	750	392.203	2,625	141.900
3	750	800	501.620	2,035	155.207
4	670	770	579.248	3,998	147.130
5	690	790	418.182	4,240	149.200

The normalized decision matrix, the standard deviation ($\boldsymbol{\sigma_i}$), the objective weight ($\boldsymbol{\tau_i}$) and Stage 3 results of VIKOR method are exhibited in Table 4.

Table 4. Normalized decision matrix, standard deviation (σ_i), objective weight (τ_i) and stage 3 results of VIKOR method for Case 1.

Normalized decision matrix			
Scenario	Flowrate	Power	Line pack
1	1.00000	0.00000	0.00000
2	0.00000	0.82210	0.08652
3	0.43208	1.00000	1.00000
4	0.73864	0.40781	0.44552
5	0.10259	0.33541	0.58770
Standard deviation (σ_i) and objective weight (τ_i) results			
Standard Deviation (σ_i)	0.42107	0.39952	0.40394
Objective weight (τ_i)	0.34386	0.32626	0.32987
Stage 3 results of VIKOR method			
Scenario	Flowrate	Power	Line pack
1	0.00000	0.32626	0.32988
2	0.34386	0.05804	0.30133
3	0.19528	0.00000	0.00000
4	0.08987	0.19321	0.18291
5	0.30858	0.21683	0.13601

The computed values the closeness coefficient, fuel consumption, and total cost are evaluated in Tables 5 and 6 to provide a comprehensive overview of the results.

Table 5. Closeness coefficient results by VIKOR method for Case 1.

Scenario	Utility(α_j)	Feasibility(ϑ_j)	Closeness coefficient(β_j)
1	0.65614	0.32987	0.90723
2	0.70323	0.34386	1.00000
3	0.19528	0.19528	**0.07533**
4	0.46599	0.19321	0.26647
5	0.66143	0.30858	0.84176

Table 6. Total fuel consumption, and Total cost values for each Scenario for Case 1.

Scenario	Total cost (M $/Yr)	Fuel consumption (klb/sec)
1	4.90	571.33
2	2.60	280.06
3	**2.10**	**217.04**
4	3.70	426.85
5	4.00	452.50

The minimum fuel consumption and optimum total cost observed in the study was determined as depicted in Figures 3 and 4.

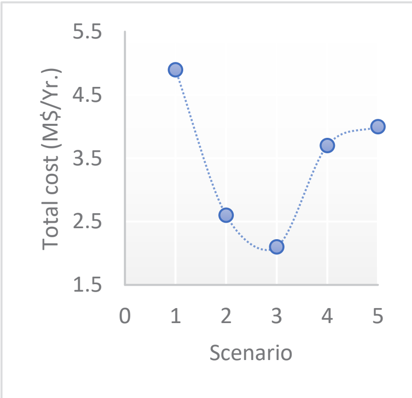

Figure. 3 Total cost (M$/yr.) of each scenario for Case 1.

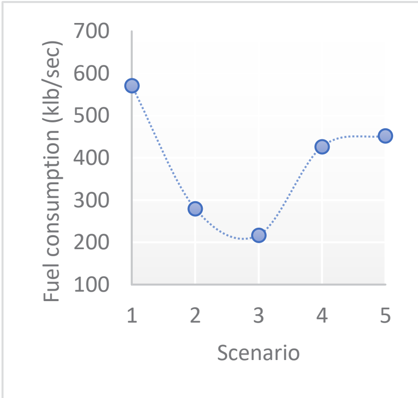

Figure. 4 Fuel consumption (klb/sec) of each scenario for Case 1.

4.6. Case 2: Branched

The pipeline network consists of twenty nodes, nineteen arcs. The length and inside diameter of each arc are shown in Table 7 (Tabkhi et al., 2009).

Table 7. Length and inside diameter data for Case 2

Arc	O.D (in)	L(mile)	Arc	O.D (in)	L(mile)
(1-2)	20	2.50	(11-12)	26	26.25
(2-3)	30	3.75	(12-13)	24	25.00
(3-4)	28	16.25	(13-14)	24	03.12
(5-6)	12	26.87	(14-15)	34	06.25
(6-7)	6	18.12	(15-16)	30	15.62
(7-4)	12	11.87	(11-17)	12	06.56
(4-14)	24	34.37	(17-18)	11	16.25
(8-9)	34	03.12	(18-19)	14	61.25
(10-11)	28	15.62	(19-20)	12	03.75
(9-10)	34	12.50			

The reference conditions for temperature and pressure are set as 520°R and 14.5 psia, respectively. The physical properties of the gas mixture employed in the system can be found in Table 2. The pipeline network is provided in Figure 5.

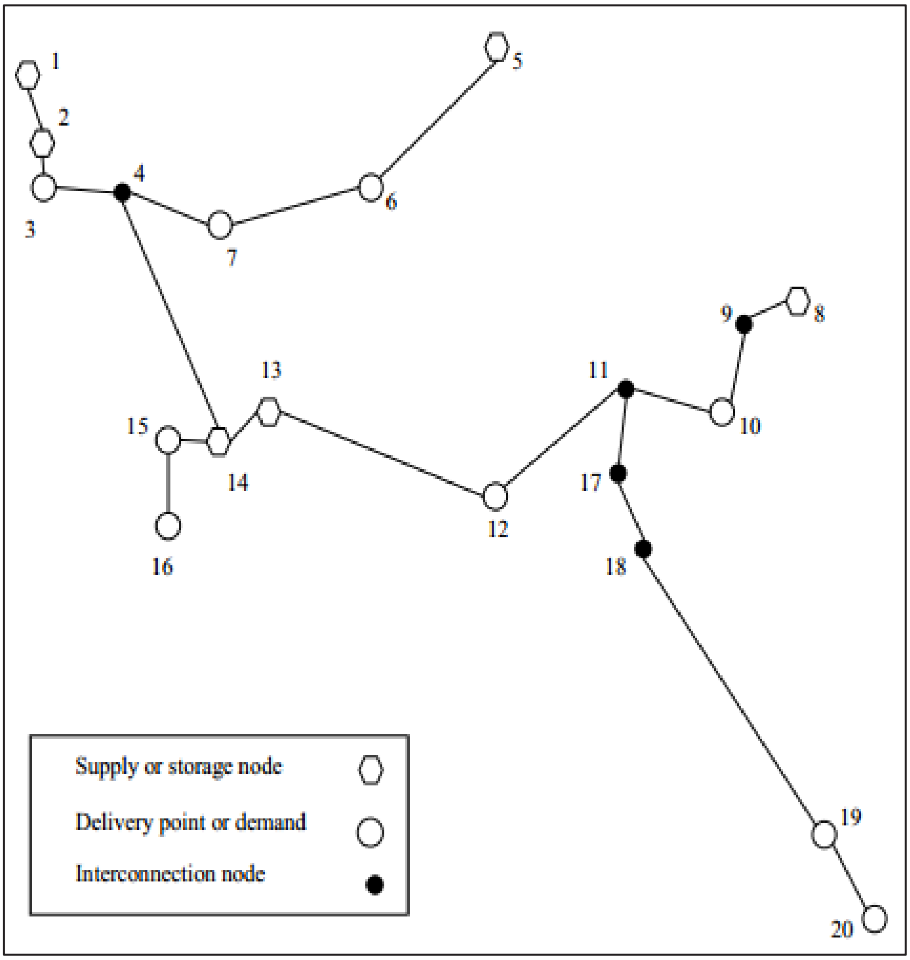

Figure 5. Pipeline network for Case 2.

Tables 8 and 9 displays data specifications, normalized decision matrix, standard deviation (σ_i), objective weight (τ_i) and Stage 3 results of VIKOR method for case 2.

Table 8. Data Specifications for Case 2

Scenario	Pmin (psi)	Pmax (psi)	Flowrate (MMscf)	Power (hp)	Line pack (MMscf)
1	420.86	1001.3	1414.36	635	6877.93
2	420.86	1117.4	963.205	396	7877.17
3	420.86	1059.4	1478.43	306	7413.52
4	420.86	1088.4	946.178	326	7533.44
5	420.86	1030.3	1446.62	623	7143.05

Table 9. Normalized decision matrix, the standard deviation (σ_i), the objective weight (τ_i) and Stage 3 results of VIKOR method for Case 2.

Normalized decision matrix			
Scenario	Flowrate	Power	Line pack
1	0.87961	0.00000	0.00000
2	0.03199	0.72678	1.00000
3	1.00000	1.00000	0.53600
4	0.00000	0.93980	0.65601
5	0.94023	0.03375	0.26532
Standard deviation (σ_i) and objective weight (τ_i) results			
Standard Deviation(σ_i)	0.50798	0.48743	0.38090
Objective weight(τ_i)	0.36908	0.35416	0.27675
Stage 3 results of VIKOR method			
Scenario	Flowrate	Power	Line pack
1	0.04443	0.35416	0.27675
2	0.35728	0.09676	0.00000
3	0.00000	0.00000	0.12841
4	0.36909	0.02130	0.09520
5	0.02206	0.34086	0.20332

Closeness coefficient results, fuel consumption and total cost are presented in Tables 10 and 11 for each scenario.

Table 10. Closeness coefficient results by VIKOR method for Case 2.

Scenario	Utility(α_j)	Feasibility(ϑ_j)	Closeness coefficient(β_j)
1	0.67534	0.35416	0.62034
2	0.45404	0.35728	0.77316
3	0.12841	0.12841	**0.00000**
4	0.48561	0.36909	0.82654
5	0.56624	0.34086	0.84163

Table 11. Total fuel consumption, and total cost values for each scenario Case 2.

Scenario	Total cost (M $/Yr)	Fuel consumption (klb/sec)
1	2.10	67.76
2	1.80	42.24
3	**1.60**	**32.64**
4	1.70	37.76
5	2.00	66.44

The minimum fuel consumption, and optimum total cost observed in the study was determined as depicted in Figures 6 and 7.

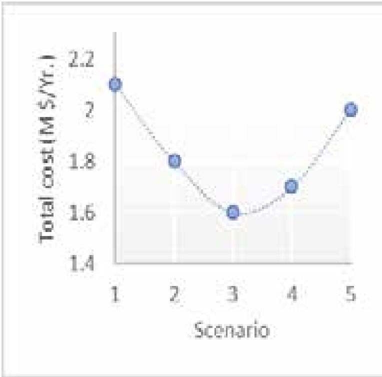

Figure 6. Total cost (M$/yr.) of each scenario for Case 2.

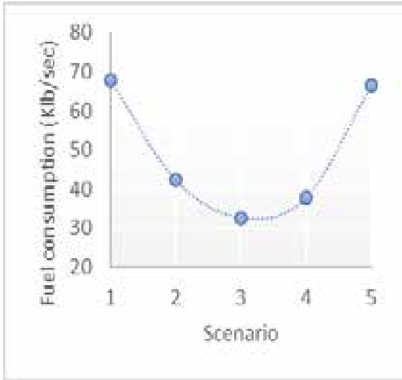

Figure7. Fuel consumption (klb/sec) of each scenario for Case 2.

4.7. Case 3: Branched cyclic

The third case study, which pertains to network characteristics, was sourced from the real-world data provided by the French Company ***GdF*** Suez (Tabkhi et al., 2010). The pipeline network is depicted in Figure 8 in a schematic manner, reflecting its multi-supply and multi-delivery nature. This case study exhibits a more intricate combinatorial aspect compared to case study 1&2 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.

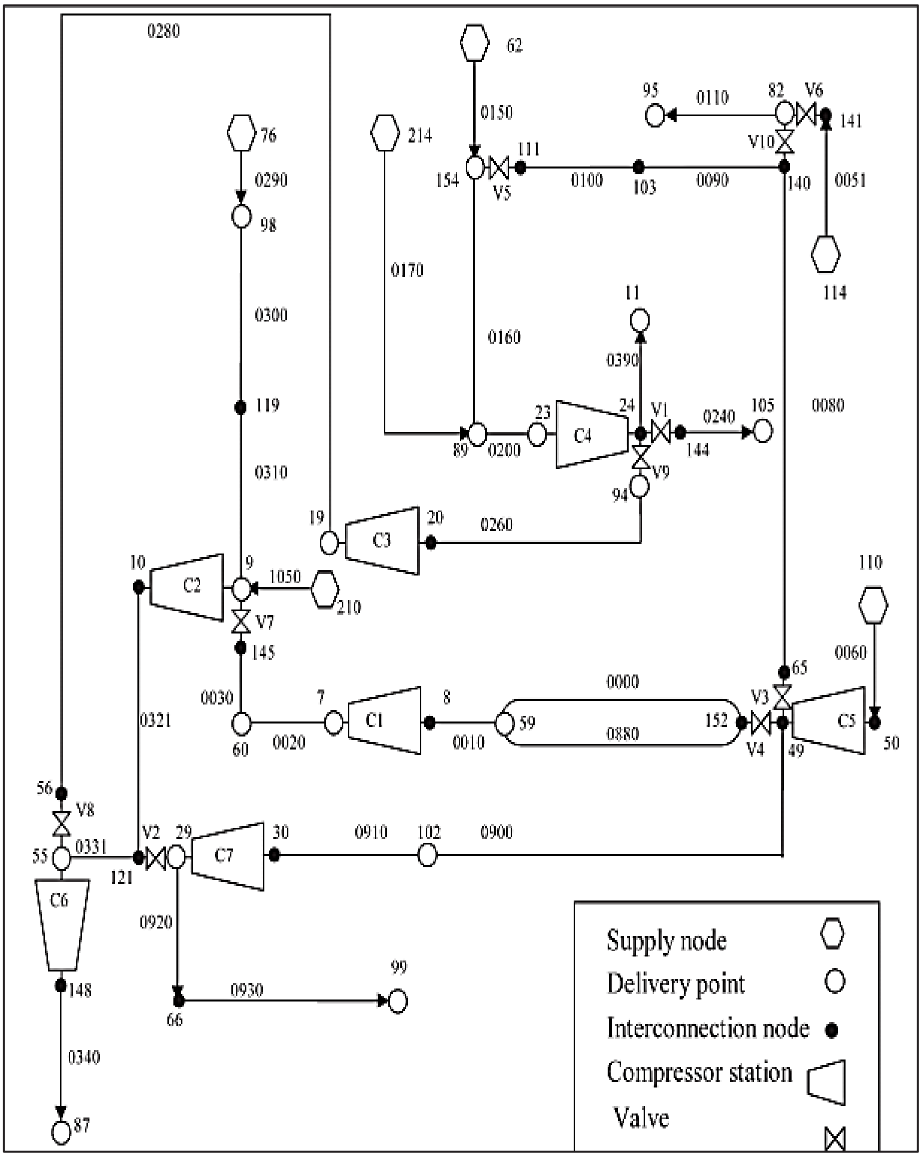

Figure 8. Pipeline network for Case 3.

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 12.

Table 12. Length and inside diameter data for Case 3

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

Tables 13 and 14 display data specifications, The normalized decision matrix, the standard deviation ($\boldsymbol{\sigma_i}$), the objective weight ($\boldsymbol{\tau_i}$) and Stage 3 results of VIKOR method for case 3.

Table 13. Data Specifications for Case 3.

Scenario	Pmin (psi)	Pmax (psi)	Flowrate (MMscf)	Power (hp)	Line pack (MMscf)
1	675	1118	216510.8	7915.5	11608.8
2	668	1147	66563.8	4157.9	12681.7
3	668	1089	67718.2	3464.5	13123.0
4	668	1176	65397.8	3524.7	12219.7
5	668	1060	162506.1	6897.0	11349.0

Table 14. Normalized decision matrix, standard deviation (σ_i), objective weight (τ_i) and Stage 3 results of VIKOR method for Case3.

Normalized decision matrix			
Scenario	Flowrate	Power	Line pack
1	1.00000	0.00000	0.14649
2	0.00772	0.84421	0.75122
3	0.01536	1.00000	1.00000
4	0.00000	0.98648	0.49080
5	0.64262	0.22883	0.00000
Standard deviation (σ_i) and objective weight (τ_i) results			
Standard Deviation(σ_i)	0.46324	0.46531	0.41403
Objective weight(τ_i)	0.34503	0.34658	0.30838
Stage 3 results of VIKOR method			
Scenario	Flowrate	Power	Line pack
1	0.00000	0.34658	0.26321
2	0.34237	0.05399	0.07672
3	0.33974	0.00000	0.00000
4	0.34503	0.00469	0.15703
5	0.12331	0.26727	0.30838

The closeness coefficient, fuel consumption and total cost results are presented in Tables 15 and 16 for each scenario.

Table 15. Closeness coefficient results by VIKOR method for Case 3.

Scenario	Utility(α_j)	Feasibility(ϑ_j)	Closeness coefficient(β_j)
1	0.60979	0.34658	0.87588
2	0.47308	0.34237	0.63050
3	0.33974	0.33974	**0.41040**
4	0.50675	0.34503	0.71221
5	0.69897	0.30838	0.51910

Table 16. Total fuel consumption, and total cost values for each scenario Case 3.

Scenario	Total cost (M $/Yr)	Fuel consumption (klb/sec)
1	15.43	383.39
2	12.24	201.39
3	**11.65**	**167.80**
4	12.51	170.72
5	14.57	334.06

The minimum fuel consumption, and optimum total cost observed in the study was determined as depicted in Figures 9 and 10.

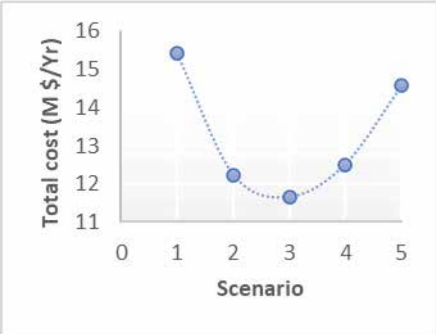

Figure 9. Total cost (M$/yr.) of each scenario for Case 3.

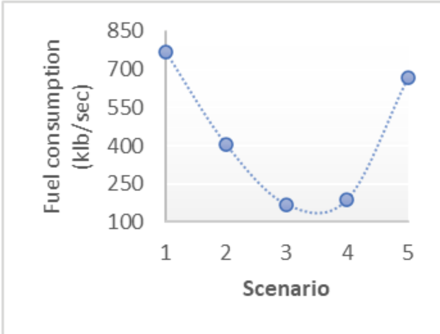

Figure 10. Fuel consumption (klb/sec) of each scenario for Case 3.

5. Results and Discussion

The results of this study demonstrate the effectiveness of the proposed multi-objective optimization model in identifying the optimal configuration for natural gas transmission networks. In each of the three cases tested, the optimal outcome was identified using the VIKOR method, confirming the model's ability to address conflicting objectives. The optimal operating properties are shown through Table 17.

Table 17. Optimal operating properties of the three cases.

Case	1	2	3
Pressure range (psi)	670-780	750-800	668-1089
Flowrate (MMscfd)	694.127	501.620	67718.2
Power (hp)	2,960	2,035	3464.5
Linepack (MMscf)	45.031	155.207	13123.0
Fuel consumption (Klb/sec)	315.81	217.04	167.80
Total cost (M$/yr)	2.70	2.1	11.65

Building upon prior research in related areas, this study introduces an innovative multi-objective optimization model that addresses conflicting objectives through a multi-criteria decision-making process. While earlier studies focused on singular objectives such as flow rate or power consumption or fuel cost, this research simultaneously considers multiple objectives, presenting a comprehensive approach to optimizing gas transmission networks. The distinct contribution lies in the utilization of the VIKOR method, setting it apart from previous approaches like TOPSIS and weighted sum methods. The VIKOR method's strengths, including simplicity and flexibility in managing diverse criteria and conflicting goals, further enhance its utility.

In essence, this study presents a fresh perspective on gas transmission network optimization, yielding insightful implications and potential advantages for the broader gas industry and beyond.

The research findings present compelling evidence of the proposed model's scalability and effectiveness in handling larger and intricate gas transmission networks, effectively identifying optimal outcomes across a diverse range of input parameters using the VIKOR method. By incorporating multiple objectives and reconciling conflicting priorities, the multi-objective optimization model offers valuable insights into resource allocation and cost-effective operation. However, it is important to acknowledge that, like any analytical approach, the VIKOR method does have certain limitations and potential drawbacks. Notably, its sensitivity to the normalization procedure, assumption of equal importance for all criteria, and lack of consideration for uncertainty and risk could impact its practical applicability. Addressing these limitations requires implementing strategic measures such as sensitivity analysis, incorporating weighting factors reflecting stakeholder preferences, and adopting probabilistic methods like Monte Carlo simulation or fuzzy logic to handle inherent uncertainties. Ensuring robustness entails validating the VIKOR method's results with real-world data and comparing them with alternative optimization approaches.

To further advance the field, future research should explore the model's scalability and explore the integration of advanced machine learning and artificial intelligence techniques for enhanced performance (D. Zhou et al., 2022). In conclusion, while the VIKOR method serves as a valuable tool for gas pipeline network optimization, strategic measures to address its limitations will enhance its reliability and practical effectiveness in real-world applications.

6. Conclusion

This paper presented a novel multi-objective optimization model for natural gas transmission networks, which considered operational considerations through a comprehensive multi-criteria decision-making process. The primary objectives of the model were to simultaneously maximize the delivery flow rate, minimize power consumption, and maximize line pack, all of which pose inherent conflicts. By employing the VIKOR method to select the optimal scenario, the model's effectiveness was demonstrated through its application to three distinct network cases.

The findings from the analysis provided significant insights into total cost and fuel consumption, rendering them highly valuable for informing decision-making processes in the natural gas transmission industry. The benefits of this multi-objective optimization approach are evident in its ability to address complex optimization problems that involve conflicting objectives, thereby offering a powerful tool for decision-makers to improve the performance and efficiency of gas pipeline networks.

Moreover, the implications of this study extend beyond the specific case studies, as the proposed approach can be adapted and applied to various other gas pipeline network optimization challenges with conflicting goals. By integrating this approach with conventional techniques, the optimization process can be further enhanced, leading to more effective and informed decision-making.

Looking ahead, future research in this field should focus on exploring alternative optimization techniques and consider additional factors such as environmental impact and safety. Addressing these factors would enhance the overall sustainability and safety of gas transmission networks. Ultimately, the development and refinement of multi-objective optimization models will contribute significantly to the efficient and sustainable operation of natural gas transmission networks in the years to come.

Appendix A

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.

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

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 Yi & Mi are the mole fractions and molecular weights of sorts, respectively.

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

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.

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

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.

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

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

Average pressure

The average pressure of gas can be calculated from the below formula by (Coelho & Pinho, 2007).

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

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.

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

Average molecular weight of gas mixture

The gas molecular weight is estimated through blending rule as:

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

Low heating value

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 considering the lower heating values of each individual gas component and their respective mole fractions in the mixture, as denoted by the subsequent equation: -

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

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: -

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

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(Mohitpour et al., 2003).

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

Nomenclature

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.
ρ_g	Is gas density in lb/ft^3.
ρ_{air}	Is air density in lb/ft^3.
D	Is pipe inside diameter in inch.
L	Is equivalent length in mile.
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.
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.
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 centrifugalcompressor (taking=0.35).
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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