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SCIENTIFIC PAPER

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SIMULTANEOUS MULTI-OBJECTIVE FRAMEWORK OF NATURAL GAS PIPELINE NETWORK OPERATIONS

Article Highlights

- TOPSIS-based multi-objective optimization is proposed
- Minimize power consumption, maximize gas flow rate, and optimize line pack
- Proven effectiveness in three case studies
- Economical gas transportation networks
- Versatile application across network scenarios

Abstract

The optimization of gas transportation networks is essential as natural gas demand increases. Conflicting objectives, such as maximizing delivery flow rate, minimizing power consumption, and maximizing line pack, pose challenges in this context. To address these complexities, a novel multi-objective optimization method based on the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is proposed. The method generates a diverse set of Pareto optimal solutions, empowering decision-makers to select the most suitable solution for gas transportation networks. Three case studies validate the approach's effectiveness, showcasing its advantages in yielding more economical networks and enhancing the cost-effectiveness of natural gas transmission networks. The proposed method's versatility allows application to various gas transportation network scenarios. Decision-makers benefit from a range of Pareto optimal solutions, providing valuable insights. Moreover, the seamless integration of the proposed method into existing gas transportation network optimization frameworks further enhances performance. In conclusion, the study presents a robust multi-objective optimization method based on TOPSIS for gas transportation network optimization. It offers cost-effective solutions and improves the efficiency of natural gas transmission networks. The provision of diverse Pareto optimal solutions enables well-informed decision-making, contributing to sustainable energy solutions in the face of increasing natural gas demand.

Keywords: gas pipeline network; multi-objective optimization; power demand; topsis; line pack; mathematical modeling.

Natural gas is gaining increasing recognition as a primary energy source for the future due to its numerous advantages, including reduced greenhouse gas emissions and lower capital costs. It has emerged as a competitive option in various sectors, particularly in newly developed power generation facilities. The importance of natural gas as a major energy exporter is evident in three key sectors: residential/commercial, industrial, and electric production. The residential/commercial sector relies on natural gas mainly for heating and cooking purposes, while the industrial sector utilizes it in diverse processes, such as chemical production and manufacturing. In the electric generation sector, natural gas is increasingly popular for power generation due to its cost-effectiveness and low emissions. Its unique properties, such as ease of

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transportation through pipelines and high energy density, contribute to its reliability and versatility as an energy source. Additionally, natural gas can be stored for extended periods, ensuring a dependable energy supply even during times of high demand or supply disruptions [1].

In summary, natural gas is a promising energy exporter for the future, offering numerous advantages. It is reliable and versatile, catering to residential/commercial, industrial, and electric production sectors. The gas industry involves production, transportation, and sales, primarily focused on pipeline networks categorized as transition and distribution. In pipeline operations, operators prioritize three key objectives: delivery flow rate, economic advantage, and line pack. Factors influencing gas delivery include production capacity, consumer demand, transmission capacity, and storage availability. Economical advantage considers purchasing costs, sales revenue, and pipeline operating expenses. Line pack refers to the stored gas volume in the pipeline. These objectives guide decision-making for efficient and cost-effective gas transportation [2].

Pipeline operations optimization aims to maximize delivery flow rate and line pack while minimizing power consumption, taking into account intricate factors at play. Designing gas transmission networks involves selecting optimal solutions to minimize costs and adhere to restrictions, using advanced mathematical techniques and modeling methodologies. The network comprises gas-collecting pipelines, transition pipelines, distribution pipelines, compressor terminals, and distribution terminals [3]. Gas assembly pipelines collect raw natural gas from output wells and transport it to treatment plants for purification. Transition pipelines then carry purified natural gas over long distances, sometimes spanning thousands of kilometers, from treatment plants to city portal terminals. Finally, distribution pipelines distribute the natural gas to end consumers. Proper planning, design, and maintenance of this critical infrastructure are essential to ensure safety and efficient natural gas transition to meet consumer demands.

In a study by Kashani and Molaei [4], a multi-objective approach was employed to optimize three opposing thematic missions: the highest possible gas delivery rate, maximum line pack, and lowest feasible operating cost. The proposed approach aims to simultaneously optimize these objectives, which may conflict with each other while considering the interdependence and complexity of pipeline operations. This multi-objective optimization enables pipeline operators to make informed decisions that strike a balance between these objectives, leading to more efficient and cost-effective pipeline operations. By considering multiple objectives, pipeline operators gain a better understanding of the trade-offs involved, aiding in the planning and execution of natural gas transmission pipeline networks, including design and operation. The main objective functions in natural gas pipeline optimization include maximizing gas delivery to specific consumers [3,5], maximizing line pack to meet peak demand and mitigate supply fluctuations [4], and maximizing economic benefit by optimizing gas sales yield and operational costs [6].

In summary, the objective function plays a crucial role in pipeline optimization, guiding the method to balance gas delivery, line pack, and economic benefit. da Silva *et al.* [7] conducted a multi-objective optimization study to assist regulatory decision-making in natural gas transition network design, considering conflicting goals of reducing transitional rent and maximizing imparted gas volume. Suet *et al.* [8] improved a multi-objective optimization process, considering uncertainties in supply conditions and consumption patterns to simultaneously reduce power request and gas supply shortage risk. Liu *et al.* [9] enhanced a dynamic pipeline network paradigm by accurately determining the compressibility factor, aiming to minimize compression costs while considering uncertainties in request and gas composition. These studies provide valuable tools for decision-makers in designing and planning natural gas pipeline networks with improved efficiency and cost-effectiveness.

The proposed approach considers uncertain gas composition and flow rates, using sequential repetitions to achieve a robust and cost-effective solution for optimizing natural gas pipeline networks. Chen *et al.* [10] developed a stochastic multi-objective optimization paradigm that accounts for uncertainties in gas demand and optimizes compressor and belowground gas store operation. The complex paradigm addresses various constraints, reducing operational costs and increasing line pack to achieve optimal solutions. Yin *et al.* [11] developed a surrogate modeling approach using machine learning to regulate flow in the process piping network. The hybrid model enhances computational speed while maintaining accuracy, leading to improved pipeline performance, cost savings, and enhanced safety. These studies offer valuable tools for decision-makers to optimize natural gas pipeline networks, considering uncertainties and enhancing overall efficiency.

Building upon the insights gleaned from the literature review, which accentuates the complexities and conflicting objectives in gas transportation network optimization.

This paper aims to tackle these challenges. The proposed methodology in this study utilizes (TOPSIS) to optimize natural gas pipeline networks, introducing innovative elements compared to prior research. Notably, TOPSIS excels in handling multi-objective optimization challenges, simultaneously addressing conflicting objectives such as gas delivery flow rate, line pack, and operating cost. The approach integrates sophisticated mathematical models and advanced simulation tools, showcasing versatility in decision-making processes. An emphasis on considering uncertainties in gas composition and flow rates, along with the utilization of sequential repetitions, enhances the robustness of the proposed solution. The versatility of the TOPSIS method itself is highlighted as it adapts to the intricacies of gas transportation network optimization.

Furthermore, the article sets itself apart by practically validating the proposed method through three case studies, demonstrating its effectiveness in achieving cost-efficiency and improved performance.

In conclusion, this study contributes significantly to the field by offering a comprehensive and innovative approach that builds upon the existing literature, providing decision-makers with a robust tool for optimizing natural gas pipeline networks.

MATERIAL AND METHODS

Formulation model for gas pipeline network

Gas pipeline network models can be constructed using a variety of mathematical techniques, such as optimization method, like linear and nonlinear programming (LP), mixed-integer linear programming (MILP), nonlinear programming (NLP), and mixed-integer nonlinear programming (MINLP), as well as graph theory and simulation models for simulating gas flow behaviour under various conditions.

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 [1]. Fig. 1 depicts the typical steps involved in the TOPSIS method that are adopted in this study.

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

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 Menon [12]. Some of these properties that are commonly calculated for gases include.

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 the universal gas constant, M is the gas's average molecular weight and relies on its composition. Gas molecular weight is estimated using the 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.

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

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 using an equation of state, this coefficient can be uttered as a function of the characteristics of the critical gas mixture T_C, average pressure P_{avg}, of the tube part and the temperature T.

$$Z = 1 + \left(0.257 - 0.533\frac{T_c}{T}\right)\frac{P_{avg}}{P_c} \tag{3}$$

The average pseudo-critical properties of the gas mixture

The pseudo-critical temperature (T_C) and pseudo-critical pressure (P_C) for natural gas can be approximated using an adequate blending rule that takes into account the critical properties of the individual components of the gas, Y_i:

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

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

Average pressure

The average pressure of gas can be calculated from the below formula [13]:

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

Specific gravity

The specific gravity of a fluid is defined as the ratio of its density to the density of a reference fluid, such as water or air, at a standardized temperature:

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

The average molecular weight of the gas mixture

The gas molecular weight is estimated through the blending rule, as

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

PIPELINE NETWORK CALCULATIONS

Pipeline volume flow rate equation

The flow equation establishes a mathematical relationship between gas flow rate Q, gas properties T_b, G, T, Z, f, pressure P_b, pipe diameter D, and the equivalent length of a horizontal pipe Le, as given by [13].

$$Q = 77.54\left(\frac{T_b}{P_b}\right)\left(\frac{P_1^2 - P_2^2}{G \cdot T \cdot Le \cdot Z \cdot f}\right) D^{2.5} \tag{9}$$

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 Mohitpour *et al.* [14]:

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon / D}{3.7}\right) \tag{10}$$

Power demand reduction

In transition systems of natural gas, compressor stations consume a significant portion of energy. Thus, decreasing their energy requirements can efficiently raise the competence of the pipeline system and the operating revenue. In addition, most compressors run on gas. Turbines decrease the energy requirement of the compressor stations which have the potential to mitigate greenhouse gas emissions, thereby contributing to environmental sustainability. Given this, it is not surprising that reducing the energy requirement of compressors is a major purpose to improve gas transition systems. Compressor stations play a critical role in the operation of natural gas pipelines, by providing the necessary energy to maintain gas flow and pressure throughout the pipeline system [4]. The energy complemented via the compressor's energy input is approximated as "head" (H), which represents the amount of energy delivered per unit mass of gas. The value of H can be obtained using Eq. (11):

$$H = ZRT\frac{K}{K-1}\left[\left(\frac{P_d}{P_S}\right)^{\frac{(K-1)}{K}} - 1\right] \tag{11}$$

where K is estimated by the Pambour equation [15]:

$$K = \frac{\sum C_{pi} M Y_i}{\sum C_{pi} M Y_i - R} \tag{12}$$

The energy transferred to the gas within the compressor can be estimated by knowing the compressor head H, gas flow rate Q and isentropic efficiency η_{is}, as described by Demissie [16]:

$$Power = \frac{Q \cdot H}{\eta_{is}} \tag{13}$$

Line pack in pipeline

Line pack LP indicates the quantity of gas that is contained within 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 uses a line pack to store excess gas. Gas is stored in pipelines during periods of low demand and subsequently discharged during periods of elevated 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 is contingent upon a multitude of factors, such as the dimensions and throughput of the pipeline, the consumption patterns of end-users, and the properties of the gas flow, such as temperature and pressure. The value of LP in MMscf is determined by using the following equation [12]:

$$LP = 7.885 \cdot 10^{-7} \left(\frac{T_{SC}}{P_{SC}}\right)\left(\frac{P_{avg}}{Z \cdot T}\right)\left(D^2 \cdot L\right) \tag{14}$$

Total cost

The total cost of a natural gas network is subject to influence by several factors such as length, diameter, pressure, and flow rate capacity requirements of the pipelines. It equals the summation of operating and fixed costs [17]:

$$Operating\ \text{cost} = 100000 + \left(Power \cdot 850\right) \tag{15}$$

Here, "*Power*" represents the power consumption in the natural gas network. It is the energy consumed by compressors, as mentioned in the discussion about power demand reduction. The operating cost includes a fixed component of 100,000 which could represent baseline operational expenses. The variable component *(Power ×850)* captures the cost associated with energy consumption, likely from compressors, as they play a crucial role in maintaining gas flow and pressure.

$$Fixed\ \ cost = (1495.4 \cdot Ln(Y_r) - 11353) \cdot D \cdot 250 \cdot \frac{L}{1600} \tag{16}$$

The fixed cost is determined by a combination of factors, and the natural logarithm of the number of years (Yr) is involved, indicating that the cost structure may be influenced by the duration of the operation. The specific constants and factors used in the equation are likely derived from empirical data or a detailed analysis of the network's characteristics and operational history.

MULTIPLE CRITERIA DECISION MAKING (MCDM)

Multiple criteria decision-making (MCDM) refers to a methodology for 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 significance of the criteria, and 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 significance of each criterion against the performance of each alternative on that criterion, and finally making the decision based on the overall evaluation. MCDM has a wide range of uses in disciplines such as finance, engineering, environmental management, and healthcare, among others, are encompassed. 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 [18]:

$$\varphi = \begin{array}{c|c} .. & \begin{array}{ccccc} \beta_1 & \beta_2 & .. & .. & \beta_n \end{array} \\ \begin{array}{c} \gamma_1 \\ \gamma_2 \\ \vdots \\ \vdots \\ \gamma_m \end{array} & \begin{bmatrix} \lambda_{11} & \lambda_{22} & .. & .. & \lambda_{2n} \\ \lambda_{21} & \lambda_{22} & .. & .. & \lambda_{2n} \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ \lambda_{m1} & \lambda_{m2} & .. & .. & \lambda_{mm} \end{bmatrix} \end{array} \tag{17}$$

where γ_i, ($i = 1,2,\dots\dots,m$) are alternative and β_j, ($j = 1,2\dots\dots,n$) are criteria for a clear view of this method. The TOPSIS method consists of a series of sequential steps that are presented next.

Step1: The most common normalization method is:

1-for max, we have:

$$\eta_{i,j} = \frac{\lambda_{ij} - \min\left(\lambda_{ij}\right)}{\max\left(\lambda_{ij}\right) - \min\left(\lambda_{ij}\right)}, \left(i \in m,\ j \in n\right) \tag{18}$$

2-for max, we have:

$$\eta_{i,j} = \frac{\max\left(\lambda_{ij}\right) - \lambda_{ij}}{\max\left(\lambda_{ij}\right) - \min\left(\lambda_{ij}\right)}, \left(i \in m,\ j \in n\right) \tag{19}$$

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

$$\mu = \begin{bmatrix} \eta_{11} & \eta_{12} & .. & .. & \eta_{1n} \\ \eta_{21} & \eta_{22} & .. & .. & \eta_{21} \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ \eta_{m1} & \eta_{m2} & .. & .. & \eta_{mn} \end{bmatrix} \tag{20}$$

Step 2: The standard deflection method estimates the weights of purposes through:

$$\tau_i = \frac{\sigma_i}{\sum_{k}^{m} \sigma_k} \tag{21}$$

$$\sigma_i = \sqrt{\frac{\sum_{i=1}^{m}\left(\lambda_i - \lambda^{-}\right)^2}{n-1}} \tag{22}$$

$$\lambda^{-} = \sum_{i=1}^{m} \frac{\lambda_i}{n} \tag{23}$$

Step 3: A set of weights *(τ1, τ2……………τn)* and $\sum_i^n \tau_i = 1$, where $\tau_i > 0$, *(i = 1, 2… n)* is given to the corresponding criterion λ_i, where *(i = 1,2,…,n)*.
The matrix $\varepsilon = \tau_i \eta_{ij}$ is calculated by multiplying the elements at each column of the matrix μ by their associated weights τ_i, *(i = 1,…,n)*.

$$\varepsilon = \begin{bmatrix} \tau_1\eta_{11} & \tau_2\eta_{12} & .. & .. & \tau_n\eta_{1n} \\ \tau_1\eta_{21} & \tau_2\eta_{22} & .. & .. & \tau_n\eta_{21} \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ \tau_1\eta_{m1} & \tau_2\eta_{m2} & .. & .. & \tau_n\eta_{mn} \end{bmatrix} \tag{24}$$

Step 4: Calculate the separation measures $(\alpha_i^{+}\ and\ \alpha_i^{-})$ between alternatives using the distance MinkowskiLp Metric as follows:

$$\alpha_i^{+} = \sqrt{\sum_{j=1}^{m}\left(\varepsilon_{ij} - \varepsilon_j^{+}\right)^2}, \left(i = 1, \ldots\ldots, n\right) \tag{25}$$

$$\alpha_i^{-} = \sqrt{\sum_{j=1}^{m}\left(\varepsilon_{ij} - \varepsilon_j^{-}\right)^2}, \left(i = 1, \ldots\ldots, n\right) \tag{26}$$

Step 5: In terms of performance evaluation of alternatives, the higher the value, the better the performance.
The optimum alternative is selected according to the greater relative closeness [18].

$$\theta_i = \frac{\alpha_i^{-}}{\alpha_i^{-} + \alpha_i^{+}}, 0 \le \theta_i \le 1 \tag{27}$$

CASE STUDIES

Case1 (linear)

The linear case consists of six nodes with three pipe arcs: (1-2), (3-4), and (5-6), forming a two-compressor network. The length of each pipe in this case is 80 km. The internal diameter of all pipes is designated as NPS 36 with a wall thickness of 0.952 cm, and a friction factor of 0.0090 is assumed. The reference values for temperature and pressure are established as 15.7 °C and 101.32 kPa, respectively. The compressors available can be represented as a tuple set ((2,3), (4,5)). Each station designated for compression in Case 1 has five centrifugal units operating in parallel [19]. The physical properties of the gas mixture in Case 1 are shown in Table 1. The pipeline network for Case 1 is depicted in Fig. 2.

Table 1. Physical properties of the gas mixture.

Gas component	C_1	C_2	C_3
Mole Fraction Y_i	0.700	0.250	0.050
Molecular mass($gmole^{-1}$)	16.040	30.070	44.100
Lower heating value at 15 °C and 1 bar (MJm^{-3})	37.706	66.067	93.936
Critical pressure (kPa)	4600	4880	4250
Critical temperature (°C)	-82.50	32.40	96.65
Heat capacity at constant pressure ($J.mol^{-1}.°C$)	35.663	52.848	74.916

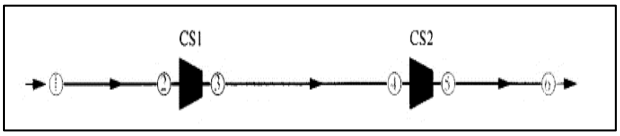

Figure 1. Pipeline network for Case 1.

Table 2 displays data specifications for different scenarios including pressure ranges, flow rate, power, and line pack for Case 1.

Table 2. Data specifications for Case 1.

Scenario	P_{min} (kPa)	P_{max} (kPa)	Flowrate (MMscf)	Power (kW)	Line pack (MMscf)
1	4136.8	5515.8	860.576	7158.7	42.022
2	4205.8	5515.8	806.789	4175.9	43.008
3	4274.7	5515.8	757.986	5644.9	45.876
4	4481.5	5171.0	576.585	2542.8	43.411
5	4619.4	5377.9	694.127	2207.2	45.031

Case2 (Tree)

This Tree case consists of ten nodes with six arcs: (2-3), (4-5), (5-6), (5-7), (8-9), and (9-10). The length of each pipe in this case is 80 km. The inside diameter of all pipes is NPS 36 with a wall thickness of 0.952 cm, and the friction factor is 0.0090. The reference temperature and pressure for the system are predetermined as 15.7 °C and 101.32 kPa, respectively. All compressor stations in Case 2, denoted by the tuple set {(1,2), (3,4), (3,8)}, are equipped with five centrifugal units operating concurrently [19]. The physical characteristics of the gas mixture in Case 2 are exhibited in Table 1. The pipeline network for Case 2 is shown in Fig. 3. Table 3 displays data specifications for different scenarios, including pressure range, flow rate, power, and line pack.

Table 3. Data specifications for Case 2.

Scenario	P_{min} (kPa)	P_{max} (kPa)	Flowrate (MMscf)	Power (kW)	Line pack (MMscf)
1	4136.8	5515.8	645.432	3989.4	140.640
2	4481.5	5171.0	392.203	1957.4	141.900
3	4619.4	5308.9	579.248	2981.3	147.130
4	4757.3	5446.8	418.182	3161.7	149.200
5	5171.0	5515.8	501.620	1517.4	155.207

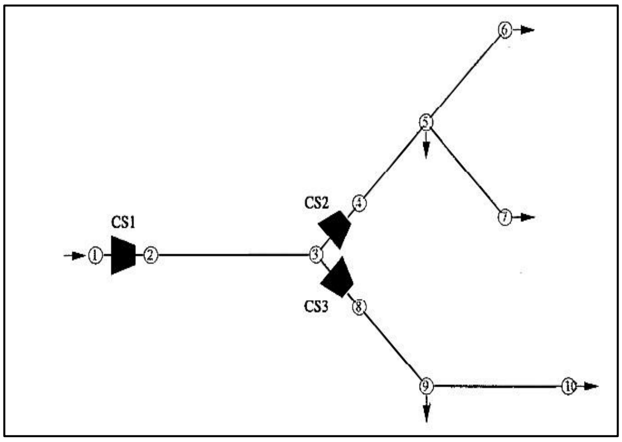

Figure 3. Pipeline network for Case 2.

Case 3 (Branched)

The Branched case consists of a pipeline network with twenty nodes and nineteen arcs. Table 4 displays the dimensions of the length and inner diameter for each arc, along with data specifications for different scenarios, including pressure range, flow rate, power, and line pack for Case 3 [20].

The reference temperature and pressure for the system in Case 3 are specified as 15.7 °C and 101.32 kPa, respectively. The relevant physical properties of the gas mixture in Case 3 have been presented in Table 1. The pipeline network for Case 3 is exhibited in Fig. 4.

RESULTS AND DISCUSSION

Hydrodynamic characterization

Table S1 (Supplementary material) contains the normalized decision matrix, standard deviation ($\boldsymbol{\sigma_i}$), objective weight ($\boldsymbol{\tau_i}$) results, and the weighted normalized decision matrix for Case 1. The normalized decision matrix result is calculated by using Eqs. (18) and (19). By using the TOPSIS method, which was presented previously, the standard deviation (σ_i) and the objective weight (τ_i) results are obtained using Eqs. (21) and (22).

In the next step, calculate the separation measures and relative closeness by using Eqs. (25–27). The total costs, which are the sum of Eqs. (15) and (16), are exhibited in Table S2.

Table 4. Data specifications, length, and inside diameter data for Case 3.

Data Specifications for Case 3					
Scenario	P_{min} (kPa)	P_{max} (kPa)	Flowrate (MMscf)	Power (kW)	Line pack (MMscf)
1	2901.7	7704.2	963.205	295.29	7877.17
2	2901.7	7504.2	946.178	243.09	7533.44
3	2901.7	7304.3	1478.43	228.18	7413.52
4	2901.7	7103.6	1446.62	464.57	7143.05
5	2901.7	6903.7	1414.36	473.51	6877.93
Length and inside diameter data for Case 3					
Arc	Diameter (cm)	Length (km)	Arc	Diameter (cm)	Length (km)
(1-2)	50.80	4.02	(11-12)	66.04	42.24
(2-3)	76.20	6.03	(12-13)	60.96	40.23
(3-4)	71.12	26.15	(13-14)	60.96	5.02
(5-6)	30.48	43.24	(14-15)	86.36	10.05
(6-7)	15.24	29.16	(15-16)	76.20	25.13
(7-4)	30.48	19.10	(11-17)	30.48	10.55
(4-14)	60.96	55.31	(17-18)	27.94	26.15
(8-9)	86.36	5.02	(18-19)	35.56	98.57
(10-11)	71.12	25.13	(19-20)	30.48	6.03
(9-10)	86.36	20.11			

The optimum scenario is the fifth one with the highest relative closeness when pressures range (4619.4:5377.9 kPa). Table S3 displays the normalized decision matrix, standard deviation ($\boldsymbol{\sigma_i}$), objective weight ($\boldsymbol{\tau_i}$) results, and the weighted normalized decision matrix for Case 2.

The separation measures, relative closeness, and total cost results are exhibited in Table S4. The

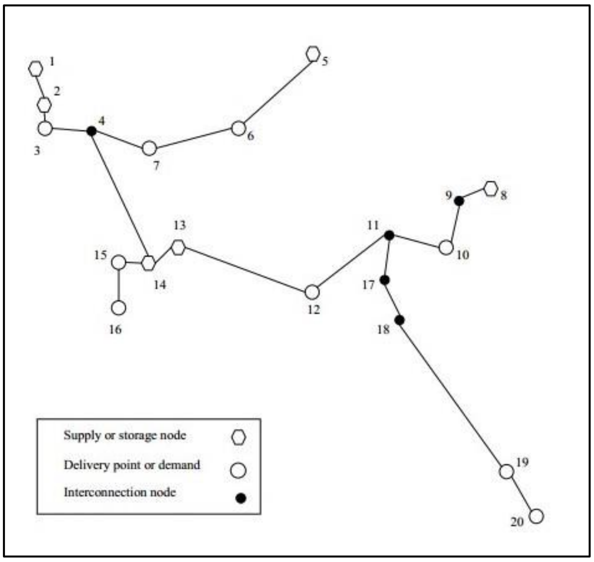

Figure 4. Pipeline network for Case 3.

(5171:5515.8 kPa).Table S5 displays the normalized decision matrix, standard deviation (σ_i), objective weight (τ_i)results, and the weighted normalized decision matrix for Case 3.

The separation measures, relative closeness, and total cost results are exhibited in Table S6. The optimum scenario is the third one with the highest relative closeness when pressures range (2901.7:7304.3 kPa). The calculations of total cost coincide with relative closeness for the three cases whereas scenarios 5 and 3 have the minimum total cost among all scenarios which confirms the accuracy, reliability, and robustness of our proposed method.

The research holds significant value by providing valuable insights into the optimization of gas pipeline networks, empowering industry stakeholders to make well-informed decisions, and enhancing efficiency, reliability, and cost-effectiveness. The proposed TOPSIS approach expands on existing multi-objective optimization techniques for gas pipeline networks in several ways. First, it integrates sophisticated hydraulic and thermodynamic models from previous studies to accurately capture the physics of gas flow. Second, it utilizes a systematic TOPSIS framework to effectively handle trade-offs between conflicting objectives. This provides an advantage over prior weighted sum methods that can struggle with balancing multiple goals [21–23].

Finally, the technique emphasizes robustness under uncertainties, leveraging sequential runs and stochastic modeling to maintain reliability - going beyond deterministic approaches. By leveraging the strengths of different methodologies, this study's TOPSIS-based technique offers a novel synthesis that enhances multi-objective optimization for gas transport.

Future research can expand on this work by exploring alternative optimization techniques, incorporating environmental impact, and safety considerations, and assessing scalability for larger and more complex gas transmission networks. Integrating advanced machine learning and artificial intelligence techniques can also enhance the model's performance.

CONCLUSION

The proposed multi-objective optimization model demonstrates significant potential for improving efficiency, reducing costs, and minimizing fuel consumption in gas transmission networks. The TOPSIS-based approach for handling conflicting objectives offers a novel and effective solution tailored to the complex challenges faced by industry. The model shows promising results in test cases, providing valuable insights into balancing total cost and fuel consumption. This simultaneously considers economic and environmental objectives to support informed decision-making. Further validation on large-scale networks is needed, but the technique shows significant potential for real-world application. The most significant implications of this study are in its ability to simultaneously optimize multiple objectives that are typically addressed separately. By considering delivery flow rate, power consumption, and line pack holistically, more optimized and sustainable solutions can be identified. The insight gained on trade-offs between total cost and fuel consumption is particularly valuable for informed decision-making by gas companies.

In summary, this work demonstrates a significant advancement in gas transmission network optimization that can overcome key limitations of current approaches. With further development, this technique can provide an advanced tool for next-generation pipeline optimization - enabling more effective modeling, planning, and management. The multi-objective technique provides a promising new tool for tackling complex pipeline optimization problems.

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NOMENCLATURE

σ_i	Standard deviation of performance rating factor (P_1j,P_2j,………Pmj) in the R matrix.
τ_i	Objective weight
P_b	Base pressure (psia)
T_b	Base temperature (°R)
P_1	Is upstream pressure (psia)

P_2	Downstream pressure (psia)
T_f	Gas flowing temperature (°R)
ρg	Gas density (lb/ft$^{3)}$
P_{air}	Air density (lb/ft$^{3)}$
D	Pipe inside diameter (inch)
L_e	Equivalent length (mile)
G	Gas gravity
T_{SC}	Suction compressor Temperature (°R)
P_{SC}	Suction compressor Pressure (psia)
R	Universal gas constant (1545 ft. lbf/lbm mol °R)
$Mwt_{(avg.)}$	Average molecular weight of gas
Mole% (i)	Mole percent of each component in gas
Mwt (i)	Molecular weight of each component in gas
T_{PC}	Pseudo critical temperature (°R)
P_{PC}	Pseudo critical pressure (psi)
Pavg	Average pressure (psi)
T	Gas temperature (K)
T_C	Critical temperature (K)
P_C	Critical pressure (psi)
K	Specific heat ratio (cp/cv) assume it to be 1.26
T_1	Suction temperature (°R)
y_i	Mole fraction of percent of gas component i, dimensionless
M_i	Molecular weight of gas component j, (g/mol)
LHV_i	Mass low heating value of molecules composing the gas (kJ/kg)
MMscf	Million standard cubic feet per day

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NAUČNI RAD

ISTOVREMENA VIŠEKRITERIJUMSKA OPTIMZACIJA RADA GASOVODA ZA PRIRODNI GAS

Optimizacija transportnih mreža gasovoda je od suštinskog značaja kako se povećava potražnja za prirodnim gasom. Konfliktni ciljevi, kao što su maksimiziranje protoka, minimiziranje potrošnje energije i maksimiziranje zaliha u gasovodima, predstavljaju izazove u ovom kontekstu. Da bi se prevazišle ove složenosti, predložena je nova metoda višekriterijumske optimizacije zasnovane na tehnici za redosled preferencije po sličnosti sa idealnim rešenjem (TOPSIS). Metod generiše raznovrstan skup Pareto optimalnih rešenja, osnažujući donosioce odluka da izaberu najpogodnije rešenje za mreže gasovoda. Tri studije slučaja potvrđuju efikasnost pristupa, pokazujući njegove prednosti u stvaranju ekonomičnijih mreža i povećanju isplativosti mreža gasovoda za prirodni gas. Svestranost predložene metode omogućava primenu u različitim scenarijima mreže gasovoda. Donosioci odluka imaju koristi od niza Pareto optimalnih rešenja koji pružaju vredne uvide. Štaviše, besprekorna integracija predložene metode u postojeće okvire za optimizaciju gasovoda dodatno poboljšava performanse. U zaključku, studija predstavlja robusnu višekriterijumsku metodu optimizacije gasovoda zasnovanu na TOPSIS-u. Nudi isplativa rešenja i poboljšava efikasnost gasovoda prirodnog gasa. Pružanje raznovrsnih Pareto optimalnih rešenja omogućava donošenje odluka na osnovu dobrog informisanja, doprinoseći održivim energetskim rešenjima u uslovima sve veće potražnje za prirodnim gasom.

Ključne reči: gasovodna mreža; višeciljna optimizacija; potreba za snagom; TOPSIS; linijski paket; matematičko modeliranje.