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Synthesis and Design of Natural Gas Transmission Networks through Fuzzy Analogical Gates

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Abstract

The escalating demand for natural gas underscores the imperative need for an optimized infrastructure facilitating the efficient transportation of gas from production hubs to end-users. This study introduces an innovative approach, employing the Fuzzy Analogical Gates methodology, to enhance the design and planning of natural gas transmission networks. The primary research objective is to achieve multi-objective optimization, prioritizing the augmentation of the delivery flowrate, the reduction of power consumption, and the maximization of line pack efficiency within the network. The proposed methodology entails a sequential application of Fuzzy Analogical Gates, commencing with the utilization of a symmetric AND gate, succeeded by an asymmetric Invoke gate, where the optimal weight index is judiciously chosen. To demonstrate the practical viability of this approach, an industrial case study is conducted, thereby verifying its real-world utility. Through the integration of Fuzzy Analogical Gates, the optimization of the design process is enriched, culminating in heightened network efficacy and performance. The inherently multidimensional nature of the optimization procedure enables a comprehensive evaluation of diverse factors, thereby ensuring optimal outcomes concerning delivery flowrate, power utilization, and line pack efficiency. In summary, this study contributes significantly to the advancement of natural gas transmission network design by introducing a pioneering methodology grounded in Fuzzy Analogical Gates. The findings underscore the potential of this technique to elevate the overall efficiency and sustainability of transmission systems. Consequently, this research offers invaluable insights into the optimization of pipeline transmission networks, thereby presenting a promising avenue for surmounting evolving challenges within this domain.

Keywords: *Fuzzy analogical gates; Mathematical modeling; Optimization network; Line pack; Pipeline optimization.*

1. Introduction

Efficient and dependable transmission of natural gas is imperative to satisfy the escalating energy requisites of contemporary societies. Given its cleaner and more abundant attributes in comparison to conventional fossil fuels, natural gas assumes a pivotal role in the global shift towards sustainable energy. The planning and enhancement of networks for transmitting natural gas involve considerations of several types of pipeline networks, each catering to specific operational needs [1]. These networks can be broadly classified into three primary categories: gathering systems, transmission systems, and distribution systems.

Gathering Systems: Gathering systems constitute networks that amalgamate natural gas from multiple production wells and channel it towards processing facilities. These systems are typically situated in regions hosting numerous gas wells in proximity. The core objective of gathering systems is to convey raw gas to processing plants, where it undergoes purification to eliminate impurities like water, sulfur, and contaminants before entering the main transmission pipelines. Gathering systems usually operate at lower pressures compared to transmission systems [2].

Transmission Systems: Transmission systems encompass high-pressure pipelines Responsible for conveying processed natural gas across vast distances, frequently covering hundreds or even thousands of kilometers. These pipelines establish connections among various locales, including production zones, distribution centers, and major industrial hubs. Due to the elevated pressure levels inherent in transmission systems, compressor stations are strategically positioned along the network to uphold gas flow and pressure. These systems serve as the fundamental framework of the natural gas distribution network, facilitating the movement of substantial gas quantities across extensive geographical spans [3].

Distribution Systems: Distribution networks are specifically designed to provide natural gas directly to end-users, including residential, commercial, and industrial customers. Operating at reduced pressures in comparison to transmission systems, these networks encompass intricate pipelines branching out to serve diverse consumers. The distribution systems exhibit the capability to cater to users with varying consumption patterns and requirements. Components such as meters, regulators, and localized distribution lines are integral to distribution systems [4].

Each of these distinctive pipeline network types presents unique challenges and optimization considerations. Gathering systems demand effective collection of gas from multiple wells while minimizing pressure losses. Transmission systems necessitate meticulous management of pressure and flow to ensure efficient gas transportation across long distances. Distribution systems require a delicate balance between supply and demand, all the while sustaining consistent pressure levels for a variety of customer segments [5].

The optimization of these networks encompasses variables such as pipeline routing, diameter sizing, optimal compressor placement, pressure regulation mechanisms, and the effective handling of flow fluctuations resulting from shifting demands. Advanced methodologies, akin to the one introduced in your initial text, hold pivotal significance in addressing the intricacies and uncertainties associated with these multifaceted factors, ultimately enhancing the comprehensive performance of these networks. The optimization and structure of transmission networks hold paramount significance to guarantee the smooth transportation of natural gas from production facilities to its final consumers [6].

Conventional methodologies for designing natural gas transmission networks have predominantly relied on deterministic models and optimization techniques. Nonetheless, these approaches often grapple with encompassing the inherent uncertainties and intricacies tied to various factors influencing network efficacy, such as erratic demands, pipeline maintenance, and supply disruptions. As a result, the need for innovative methodologies adept at managing these uncertainties and delivering robust solutions is increasingly evident [7-8].

Recent years have witnessed the integration of fuzzy logic and analogical reasoning as promising tools to tackle imprecision and uncertainty across diverse scientific and engineering spheres. Fuzzy logic presents a robust framework for articulating and manipulating ambiguous and fuzzy concepts, facilitating the modeling of uncertain variables within gas transmission – encompassing factors like pressure, flow rate, and demand. Analogical reasoning, on the other hand, leverages resemblances between existing network configurations and potential designs to deduce novel insights and enhance system performance [9].

This study introduces an inventive approach amalgamating fuzzy logic and analogical gates for the formulation and design of natural gas transmission networks. By harnessing the inherent adaptability and interpretability of fuzzy logic, this technique endeavors to adeptly manage the uncertainties and imprecision inherent in gas transmission variables. The incorporation of analogical gates enables the identification of analogous network configurations and knowledge transference from established systems to novel designs, thereby augmenting the efficacy and dependability of the resultant network. The primary goal of this investigation is to proffer a comprehensive methodology that encompasses the establishment of fuzzy logic rules, the integration of analogical gates, and the optimization of network parameters within natural gas transmission systems. A practical A case study is provided to illustrate how the suggested approach can be practically applied to a real-world natural gas transmission network, underscoring its effectiveness in navigating uncertainties and elevating network performance [10].

In summary, the objective of this paper is the integration of fuzzy analogical gates in the synthesis and design of natural gas transmission networks offers a compelling avenue for the development of robust and efficient gas transportation systems. This approach acknowledges and accommodates the inherent uncertainties and complexities inherent in gas transmission, offering the prospect of enhancing the dependability, adaptability, and environmental sustainability of natural gas supply networks. Ultimately, this research contributes to advancing the trajectory towards a cleaner and more sustainable energy future.

2. Methodology

The utilization of the fuzzy analogical gate method involves the application of analogical reasoning to enhance decision-making across various contexts. This method leverages the similarities between familiar situations and new scenarios, allowing for the extraction of insights and informed decision-making [11]. This approach is particularly advantageous when dealing with complex and uncertain situations which may not be effectively addressed using conventional analytical methods. Subsequently, the resulting networks undergo the application A set of analogical gates with a fuzzy nature, including both symmetric and asymmetric variations. The symmetric gate, often referred to as the AND gate, takes normalized flowrate and line pack as inputs. On the other hand, the asymmetric gate, known as the Invoke gate, takes inputs from the AND gate and normalized power demand. The stages depicted in Fig.1., typically associated with the calculation of total costs.

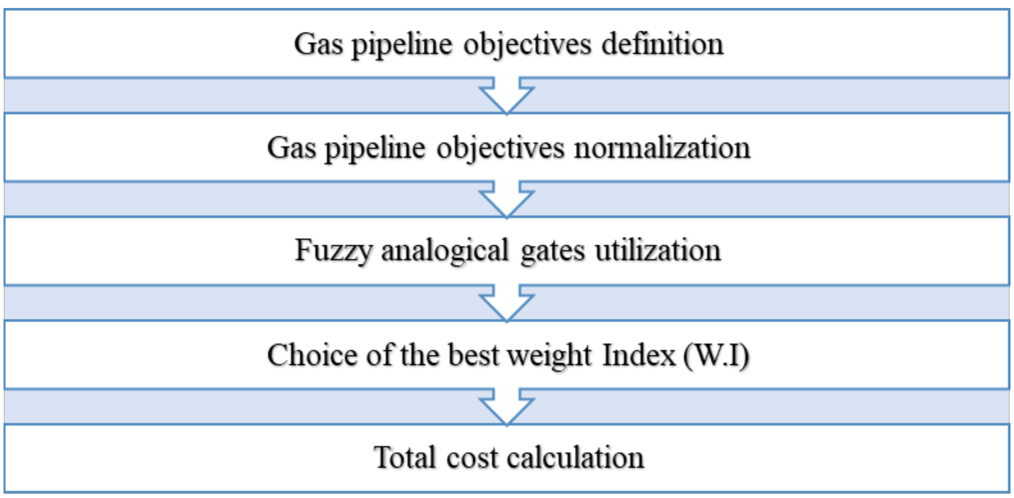

Fig. 1. Flow chart of typical steps involved in the FUZZY analogical gate.

3. Development of a model for gas pipeline network formulation

Various mathematical approaches, including optimization techniques like linear (LP) and nonlinear programming (NLP), mixed-integer linear programming (MILP), and mixed-integer nonlinear programming (MINLP), as well as methods such as graph theory and simulation models, can be employed in the construction of models for gas pipeline networks. These models aim to simulate the behavior of gas flow under different conditions. The choice of the suitable mathematical technique and optimization or simulation method depends on the specific attributes of the network [12].

3.1. Gas properties

To effectively analyze and predict the behavior of gases in diverse practicalities like process design, combustion analysis, and gas transportation, a solid grasp of gas properties is essential. The assessment of these characteristics hinges on essential principles derived from fluid dynamics, molecular theory and thermodynamics, as emphasized by Menon [16]. A portion of these characteristics commonly calculated for gases are exhibited in Appendix A.

3.2.Calculations related to pipeline networks

3.2.1. Equation for the volumetric flow rate in pipeline

The flow equation establishes a mathematical relationship between gas flow rate, gas properties, pressure, pipe diameter, and the equivalent length of a horizontal pipe, as given by [13].

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

3.2.2. Power demand reduction

Within natural gas transmission systems, compressor stations hold a pivotal function, yet they consume a substantial amount of energy. By diminishing their energy usage, the efficiency of the pipeline system can be greatly improved, leading to increased operational revenue. These stations are indispensable for sustaining the flow and pressure of natural gas across the pipeline network [14]. The energy provided by the compressor's input is measured as "head" (H), which signifies the energy imparted for each unit mass of gas. The calculation of H can be accomplished using Eq. (2).

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

where K is determined using the Pambour method [14].

$$K = \frac{\sum C_{pi} MY_i}{\sum C_{pi} MY_i - R} \quad (3)$$

The energy transferred to the gas inside the compressor can be approximated using the Demissie method [15].

$$Power = \frac{Q.H}{\eta_{is}} \quad (4)$$

3.2.3. Pipeline line pack

Line packs refers to the volume of gas within a pipeline, essential for sustaining system pressure and accommodating shifts in demand. It's value is measured by [16], in million standard cubic feet (MMscf) and can be calculated using Eq. (5),.

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

3.3. Overall cost

The complete expense of a natural gas network can be affected by various elements. It is equivalent to the combination of operational and fixed expenses [17].

$$Operating\ Cost = 100000 + (Power \times 850) \quad (6)$$

$$Fixed\ Cost = (1495.4 \times Ln(Yr) - 11353) \times D \times 250 \times \frac{L}{1600} \quad (7)$$

3.4. *Fuzzy analogical gates strategy*

The process for determining the optimal weight index involves three consecutive stages [18]:

Step1: Calculation of the standardized variables parameters such as maximum gas delivery, maximum line pack and minimum power consumption.

1- for max, we have

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

2- for min, we have

$$\eta_{ij} = \frac{max(\theta_{ij}) - \theta_{ij}}{max(\theta_{ij}) - min(\theta_{ij})} \ , \ (i \in m \ \ , j \in n) \quad (9)$$

Step 2: Two sequential fuzzy analogical gates will be employed, as depicted in Figures 2 and 3. The initial gate chosen is symmetrical, while the subsequent one is asymmetrical. Following

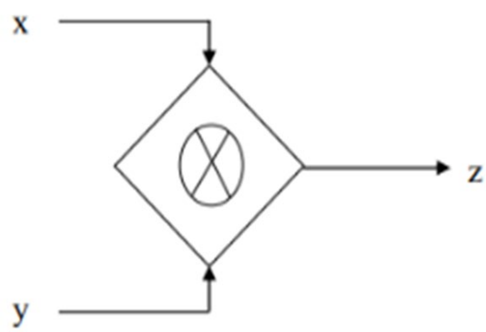

Fig. 2. Symbols for the analogical AND gate.

the fuzzy analogical AND gate, a fuzzy Invoke gate will be utilized. Within the fuzzy analogical-AND gate, the output experiences the most significant increase when both inputs grow simultaneously. Furthermore, no output is generated if either input is zero.

$$z = x \otimes y = x[1 - \xi(y,x)] + y[1 - \xi(x,y)] \quad (10)$$

Certainly, the function ξ can be considered as the membership function of a fuzzy relation, and it is determined by the following exponential expression:

$$\xi(y,x) = exp\left[\frac{ay^2 + byx}{y^2 + x^2}\right] \text{ and } x,y \in R \quad (11)$$

$$\xi(x,y) = exp\left[\frac{ax^2 + bxy}{y^2 + x^2}\right] \text{ and } x,y \in R \quad (12)$$

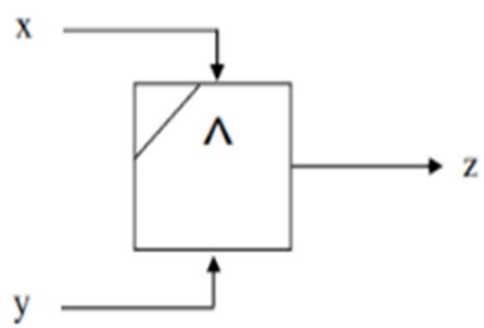

Fig. 3. Symbols for the analogical Invoke gate

The values for parameters a and b can be derived by applying boundary conditions and ensuring zero derivative along the principal axis values of a and b are 2.28466 and -0.089817, respectively. The invoke gate is defined by the property that as the x-input increases, the contribution of the y-input to the output also increases. When there is no x-input, the output is suppressed. Similarly, if there is no y-input, the x-input is directly transmitted to the output in a linear manner [19]. The graphical representation of the analogical Invoke gate symbols is depicted in Figure 3.

$$z = x \wedge y = x\xi_1[(y,x)] + y[1 - \xi_2(x,y)] \quad (13)$$

Here, ξ_1 and ξ_2 can be seen as the membership function of a fuzzy relationship and are described by the subsequent exponential function:

$$\xi_1(y,x) = exp\left[\frac{-(a_1y^2 + b_1yx)}{y^2 + x^2}\right] \text{ and } x,y \in R \quad (14)$$

$$\xi_2(x,y) = exp\left[\frac{-(a_2x^2 + b_1xy)}{x^2 + y^2}\right] \text{ and } x,y \in R \quad (15)$$

where: a_1=1.4749267; b_1=0.92870491; a_2=2.6317713; b_2=0.2287955.

Step 3: Selecting the optimal weight index (W.I).

This process entails evaluating all weight index values and selecting the highest one.

$$W.I_{optimum} = \max\{W.I_1, W.I_2, W.I_3, \ldots W.I_n\} \quad (16)$$

4. Case study (Multi input-Multi output)

This case study, which centers on the network's attributes, derives its foundation from authentic data supplied by the *French Company GdF Suez*. Additionally, the physical characteristics of the gas mixture are delineated in Table 1.

Table 1. Physical Properties of gas mixture.

Gas component	C1	C2	C3
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 (bar)	46.000	48.800	42.500
Critical temperature (K)	190.60	305.40	369.80
Heat capacity at constant pressure $(\mathrm{J.mol}^{-1}.\mathrm{K})$	35.663	52.848	74.916

Table 2. Length and outside diameter data.

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

Table 3. Data specifications for different scenarios.

Scenario	P_{min} (psi)	P_{max} (psi)	Flowrate (MMscf)	Power (hp)	Line pack (MMscf)
1	668	1060	162506.2	6,897	11348
2	668	1176	67718.16	3,465	13123
3	668	1089	216510.8	7,916	11608
4	668	1147	66563.84	4,158	12681
5	675	1118	65397.79	3,525	12219

The initial conditions prescribe a baseline temperature of 520°R and a pressure of 14.5 psia. Fig. 4 provides a schematic representation of the depicted transmission network, illustrating its intricate nature with numerous origins and destinations.

Comprehensive information regarding the dimensions of length, internal diameter, and surface roughness for each pipe can be located in Table 2 [20].

Table 3 presents data specifications for various scenarios, encompassing flowrate, power, and line pack.

Table 4. The normalized flowrate, power, line pack, and weight index results.

Scenario	Flowrate	Power	Line pack	Weight Index
1	0.64262	0.22883	0.00000	0.000000
2	0.01536	1.00000	1.00000	0.000198
3	1.00000	0.00000	0.14649	0.044525
4	0.00772	0.84421	0.75122	0.000066
5	0.00000	0.98648	0.49080	0.000000

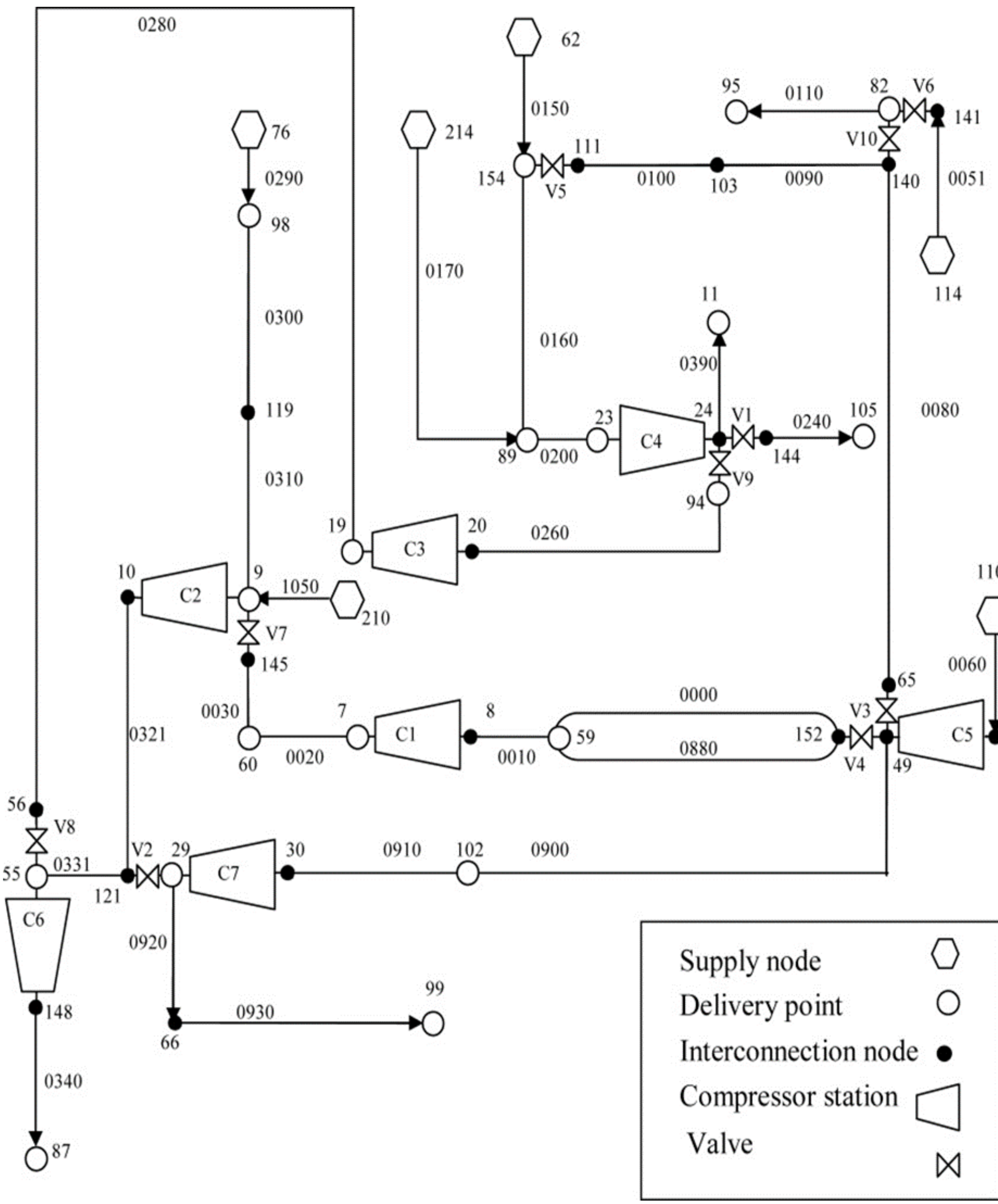

Fig. 4. Pipeline network (by courtesy of Gaz de France).

5. Results and discussion

This case presents a heightened level of complexity due to the presence of 7 compressor stations and 3 loops within the system. The network is comprised of 19 delivery points in total, represented as small vacant circles, which serve as gas extraction sites. Gas can be obtained from 6 distinct locations, depicted as hexagons. Furthermore, the network includes 20 intermediary nodes that facilitate connections and occasionally influence design parameters. In total, the network consists of 45 nodes and 30 pipe segments. Additionally, seven strategically placed compressors are employed to counter pressure losses. The fuzzy analogical gates, comprising both symmetric and asymmetric gates, consist of two analogical gates. The symmetric gate, known as the AND gate, takes the normalized flowrate and line pack as inputs. On the other hand, the asymmetric gate, referred to as the Invoke gate, receives inputs from the output of the AND gate and the normalized power demand.

To normalize the flowrate, power, and line pack, Eq. (8) and (9) have been applied, while Eq. (17) has been used to calculate the weight index. The detailed results are presented in Table 4 for reference. In the ongoing analysis, the next step involves calculating separation metrics and evaluating relative proximities. The total costs which are the sum of Eq. (6, 7) are presented in Table 5.

Table 5. Total cost calculations for each scenario.

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

The optimal arrangement is illustrated by the initial scenario, showcasing the highest degree of relative proximity within the pressure range of 668 to 1089 pounds per square inch (psi). The mathematical computations related to the total cost provide validation for the robustness of our proposed methodology. This validation is exemplified by scenario 3, which presents the most economical cost among all the scenarios considered.

6. Conclusion

This research introduces a novel multi-objective optimization model for designing natural gas transmission networks, incorporating operational considerations through fuzzy analogical gates. The model aims to simultaneously maximize delivery flowrate, minimize power consumption, and maximize line pack three conflicting objectives in network design. The model's effectiveness is demonstrated through three distinct network scenarios analyzed using fuzzy analogical gates to select optimal solutions. Results indicate the model's capability to produce cost-effective and efficient network designs while accommodating multiple objectives and operational constraints. This approach offers a two-fold advantage. Firstly, it establishes a comprehensive framework for addressing optimization challenges in gas pipeline networks with conflicting objectives. By optimizing critical performance metrics like flowrate, power consumption, and line pack simultaneously, the approach creates networks balancing efficiency and operational requirements. Secondly, the integration of fuzzy analogical gates improves decision-making by utilizing similarities and knowledge from existing network configurations. This results in well-informed design choices, enhancing network performance and reliability. The research's implications extend beyond natural gas transmission networks, adaptable to optimization challenges across gas pipeline networks. Future studies could explore its integration with conventional techniques for further optimization gains. To advance the field, considering alternative methodologies and broader factors like environmental impact and safety is important. Overall, the proposed multi-objective optimization model, incorporating fuzzy analogical gates, offers an effective approach for designing natural gas transmission networks, enhancing network efficiency, reliability, and sustainability by addressing conflicting objectives and leveraging analogical reasoning.

Appendix A

Gas Density

The connection between gas density and pressure, as illustrated in the given Eq., is established by employing the compression coefficient denoted as *Z* within the framework.

$$\rho = \frac{PM}{ZRT} \quad \text{(A.1)}$$

In this context, the universal gas constant is represented by "*R*," while the average molecular weight of the gas, denoted as "*M*," is contingent upon its composition. The determination of gas molecular weight is accomplished through a straightforward blending rule, outlined in the subsequent Eq., where "Y_i" and "M_i" signify the mole fractions and molecular weights of the respective components.

$$M = \sum M_i Y_i \quad \text{(A.2)}$$

Compressibility factor

The compressibility factor often referred to as the compression coefficient denoted by *Z*, is employed to modify the ideal gas Eq. to account for the behavior of real gases. Traditionally, this coefficient is calculated using an equation. of state. It can be formulated as a function of essential gas mixture characteristics, the mean pressure within the pipeline segment, and the current temperature.

$$Z = 1 + \left(0.257 - 0.533\frac{T_C}{T}\right)\frac{P_{avg}}{P_C} \quad \text{(A.3)}$$

The mean pseudo-critical attributes of the gas blend

It can be calculated using an appropriate mixing rule that takes into account the critical properties of gas components.

$$T_{PC} = \sum T_{Ci} Y_i \quad \text{(A.4)}$$

$$P_{PC} = \sum P_{Ci} Y_i \quad \text{(A.5)}$$

Mean gas pressure

The mean pressure can be determined using the following formula [13].

$$P_{avg} = \frac{2}{3}\left(P_1 + P_2 - \frac{P_1 * P_2}{P_1 + P_2}\right) \quad \text{(A.6)}$$

Relative density

The relative density of a fluid is described as the proportion of its density to the density of a standard reference fluid, at a specified temperature.

$$S_g = \frac{density\ of\ gas}{density\ of\ air} = \frac{M_{gas}}{M_{air}} \quad \text{(A.7)}$$

Average molecular weight of gas mixture

The gas molecular weight is estimated through blending rule as

$$M_{wt\ (avg.)} = \sum M_i Y_i \quad \text{(A.8)}$$

Friction factor

The friction factor (*f*) within pipeline flow is a non-dimensional measure that signifies the resistance encountered due to factors like pipeline surface roughness, turbulence, and viscosity. This parameter carries significance in both pipeline design and operation, impacting pressure decline and energy dissipation. Its determination can be achieved through empirical Eq.

or data from experiments. The Nikuradse Eq., commonly employed for friction coefficient estimation This implicit Eq. connects the friction factor to pipeline surface roughness (ε) and pipeline diameter (D). The Nikuradse Eq. represents this relationship as follows [21].

$$\frac{1}{\sqrt{f}} = -2log\,(\frac{\frac{\varepsilon}{D}}{3.7}) \qquad (A.9)$$

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Nomenclature

P_b	base pressure in psia.
T_b	base temperature in °R.
P_1	upstream pressure in psia.
P_2	downstream pressure in psia.
T_f	gas flowing temperature in °R.
ρ_g	gas density in lb/ft^3.
ρ_{air}	air density in lb/ft^3.
D	pipe inside diameter in inch.
L	equivalent length in mile.
$M_{wt\,(avg.)}$	average molecular weight of gas.
T_{PC}	the pseudo critical temperature °R.
P_{PC}	the pseudo critical pressure psi.
P_{avg}	average pressure in psi
T	gas temperature in k.
T_c	the critical temperature in k.
P_c	the critical pressure in psi.
K	specific heat ratio (cp/cv) assume it to be 1.26.
T_1	suction temperature in °R.
Y_i	mole fraction of percent of gas component i, dimensionless.
M_i	molecular weight of gas component (i), in g/mol.
MMSCFD	Million standard cubic feet per day.

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