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Optimization of Multi-Component Gas Mixture in Pipeline Transmission Network using General Algebraic Modeling System

Rozan. M. Kamal[1*], S. M. Aly[2], Galal Mohamed Abdelalim [2]

[1]*Canal High Institute of Engineering and Technology, Suez, Egypt.*

[2]*Department of Refining and Petrochemical Engineering, Faculty of Petroleum and Mining Engineering, Suez University, Suez, Egypt.*

Abstract

The increasing reliance on fossil fuels and the consequent surge in harmful emissions have stimulated widespread investigation into alternative fuel options. As a response to these challenges, natural gas has emerged as a comparatively cleaner and ecologically substitute for energy. This research paper focuses on the cost-effectiveness of transmitting natural gas through pipeline networks. It includes three case studies from previous work with different network topologies: linear, branch, and cyclic. The innovative network optimization techniques involve the integration of the General Algebraic Modeling System (GAMS) and the fuzzy multi-criteria decision analysis technique (FMCDA) in the research. GAMS is employed to determine the optimal pipe diameters and compressor locations, considering specific constraints such as flow rate, pressure range, and pipe length. On the other hand, FMCDA is utilized to identify the most efficient solution scheme by considering objectives such as maximizing line pack, minimizing compressor power, and reducing fuel consumption. The research shows that optimized models can determine the optimal objective function for natural gas pipeline networks, leading to cost reduction. For example, a linear topology with a flow rate of 17 MMSCMD and a pipe with an optimum diameter of 36 inches reduced the total cost to $292 million per year. The branched topology, with the same flow rate but with a shorter length, required less power so the cost was reduced to $78 million per year. While the cyclic topology, with a higher flow rate of 28 MMSCMD, required more power, achieving a total cost of 327 million dollars per year.

Keywords: Crucial Infrastructure; Cost Reduction; Fuzzy Approach; GAMS; Mathematical Model; Optimal Design Pipeline

1 Introduction

The ever-increasing global demand for energy, coupled with the depletion of fossil fuel reserves and the ecological consequences of greenhouse gas emissions, has stimulated a rigorous exploration of alternative fuel alternatives [1]. Consequently, the world is progressively moving towards a critical energy predicament [2]. Natural gas has emerged as a superior and ecologically compatible alternative energy source, showcasing heightened cleanliness and enhanced environmental friendliness [3]. It primarily consists of over 90 % methane (CH_4), accompanied by ethane and a minor proportion of other hydrocarbons [4]. It offers abundant and clean energy, versatility in its usage, high energy efficiency, reliable supply, economic benefits, and the potential for energy storage [5]. These advantages make natural gas a preferred energy source, providing a reliable, efficient, and environmentally friendly solution for various energy needs [6].

This scholarly article offers an extensive analysis of the notable research conducted to tackle the complexities linked to the conveyance of natural gas via pipeline systems. The available literature expounds upon the three principal classifications of gas pipeline systems, namely gathering, transmission, and distribution systems [7]. The gathering involves collecting and transporting gas to processing plants, while transmission involves long-distance transportation to demand midpoints. Distribution is responsible for delivering natural gas to end consumers, including suburban, commercial, and industrialized users [8]. This network includes gas sources, delivery points, pipelines, compressors, and various equipment necessary for its operation, such as valves and regulators [9],[10].

Natural gas pipelines can be further classified based on the arrangement and structure of their network topologies. The linear topology consists of compressor stations arranged linearly. In a tree topology, the compressors are structured in a branching pattern, while in a cyclic topology, the compressors establish interconnected cycles with other compressor stations [11]. Optimizing the gas pipeline network is a critical field of study focused on enhancing the effectiveness and dependability of gas distribution to end consumers [12]. This procedure entails methodically enhancing the structure and functioning of the network to attain optimum performance, cost-efficiency, and effective resources.

In recent times, scientists have investigated various methodologies to tackle the optimal problem associated with natural gas pipeline networks. These techniques encompass mathematical programming, genetic algorithms (GA), particle swarm optimization (PSO), simulated annealing

*Corresponding author e-mail: rozanmohamed25494@gmail.com.; (Rozan. M. Kamal).
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(SA), and dynamic programming [13]. The problem formulation and identification of optimal solutions have been facilitated through the utilization of mathematical programming techniques, specifically mixed integer linear programming, and non-linear programming [14]. GA, PSO, and SA optimization have been used as meta-heuristic optimization techniques to search for optimal solutions [15]. Dynamic programming has been employed to iteratively calculate the optimal value function and control policy for each state in a recursive manner [16]. Moreover, optimization of gas pipelines can be obtained by using fuzzy approach techniques. The utilization of fuzzy logic methodologies to improve the effectiveness and functionality of gas pipeline networks [17]. These methodologies incorporate the utilization of fuzzy sets and fuzzy reasoning to model and assess complex and uncertain variables, such as flow rates, pressure levels, and pipeline conditions. By employing fuzzy approach techniques, operators can make more knowledgeable determinations about pipeline operations, maintenance, and resource allocation [18]. This optimization methodology strives to maximize the utilization of pipeline capacity, minimize energy consumption, decrease operational expenses, and guarantee the secure and dependable transportation of natural gas [19]. Several research investigations focus on the examination of decision-making processes employing fuzzy logic [20]. These studies explore the application of a multi-objective fuzzy linear programming model, which considers both economic and environmental objectives. Additionally, another study [21] introduces fuzzy linear programming as an approach to cost minimization, providing expedited and adaptable solutions in comparison to traditional linear programming methods. Some other studies discuss the utilization of GAMS to optimize natural gas pipeline networks through the formulation and resolution of intricate mathematical models [7]. GAMS offers simplified representation, and diverse optimization techniques, and facilitates efficient solutions, leading to cost reduction, enhanced performance, and dependable gas transportation [22]. Most previous research [23] examines the necessity of optimization software and tools to effectively manage the escalating complexity of forthcoming advanced grids. It emphasizes the suitability of GAMS as an optimal choice for optimizing extensive systems, given its solvers and adaptability to evolving energy network scenarios. The objective is to explore the application of GAMS in constructing sustainable models for the modernization of grids.

Prior studies [22] underscore the significance of optimization software in effectively handling the escalating intricacy of advanced grids. It accentuates the appropriateness of GAMS owing to its solvers and flexibility in adapting to evolving energy network scenarios. The aim is to employ GAMS in constructing sustainable models for the advancement of grid systems.

This paper focuses on the transmission of a multi-component gas mixture, primarily This manuscript focuses on the enhancement of natural gas transmission efficiency in pipeline networks through the utilization of GAMS and fuzzy multi-criteria decision-making techniques. The investigation addresses the challenges associated with a multi-component gas mixture, encompassing methane, ethane, propane, and butane, which exhibit diverse thermodynamic properties and flow characteristics. The efficiency, reliability, and cost-effectiveness of three pipeline configurations, namely linear, branched, and cyclic topologies, are thoroughly analyzed. Mathematical modeling and optimization methods are employed to maximize line pack and minimize power and fuel consumption. The GAMS model determines the optimal diameter by considering flow capacity, initial cost, and pressure drop. Furthermore, the optimal compressor location is determined based on distance, elevation changes, and operational constraints. Fuzzy multi-criteria decision-making techniques are employed to promote sustainability and cost-effectiveness during the optimization process. The integration of GAMS and fuzzy multi-criteria decision analysis technique (FMCDA) is the novelty of the paper that facilitates the identification of the most efficient solution scheme, taking into account objectives such as maximizing line pack, minimizing compressor power, and reducing fuel consumption. The concise of this paper is shown in Figure (1).

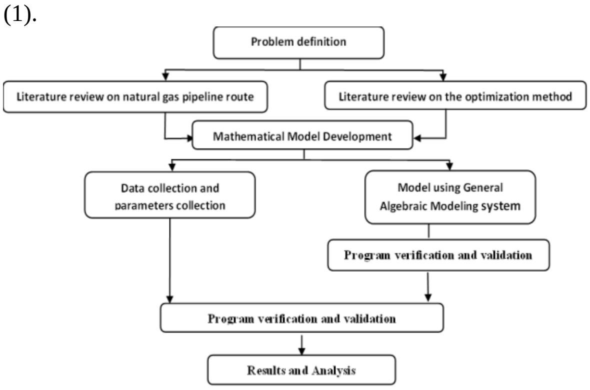

Fig. (1) The concise of this paper

2 Materials and Methodology

Our model is solved using GAMS with the help Fuzzy approach to multi-criteria decision-making.

2.1 Materials

2.1.1 *General Algebraic Modeling System*

GAMS is a software tool used for modelling and solving optimization problems. Originally developed for water resources management, GAMS has since been expanded to various applications, including natural gas pipeline networks. It allows users to formulate mathematical models that represent the components and constraints of the network and solve optimal solutions given these constraints. GAMS is versatile and can handle linear, nonlinear, and complex models, making it a valuable tool for investigating and optimizing complex systems such as water resources and natural gas pipeline networks [24]. After nearly three decades of advancement, GAMS has demonstrated successful application in mathematical optimization problems across diverse domains. It demonstrates substantial advantages in terms of comprehensiveness, stability, and user-friendliness in generating optimization solutions. [25]. The optimization model includes five key components Figure (2) [26]:

1. The sets as a collection of nodes
2. All of the model's parameters
3. All variables
4. The names of the equations and their mathematical structures
5. The model's nature (i.e., MINLP)

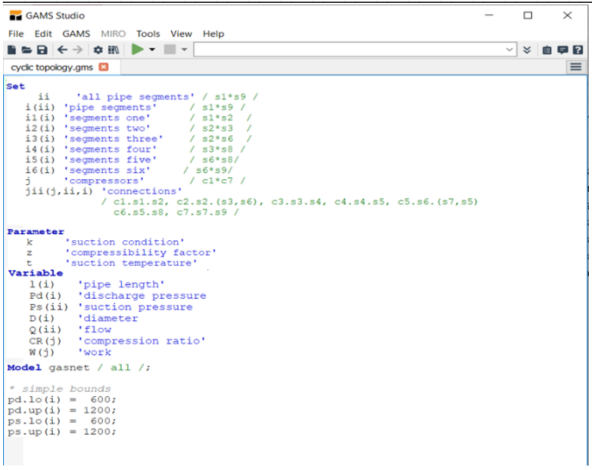

Fig. (2) GAMS model

2.1.2 *Fuzzy approach multi-criteria decision making (MCDM)*

MCDM is a systematic approach used to assess and rank alternatives in complex decision problems with conflicting criteria. It aids decision-makers in considering various factors and their interrelationships for informed decision-making [27]. MCDM are frequently employed in the context of energy decision-making problems. To enhance accuracy, the fuzzy set theory (FST) can be integrated with MCDM methods. FST represents uncertainties in human opinions, allowing a comprehensive evaluation of alternatives from different perspectives. This integration improves the reliability and practicality of outcomes in energy-related decision-making [28].

Zadeh (1965) initially introduced fuzzy set theory for industrial controller applications, and its application has since extended to diverse fields including engineering, operational research, mathematics, expert systems, pattern recognition, robotics, medicine, and computer science [29]. The potential of FST lies in its ability to revolutionize risk analysis and risk assessment of safety systems in regions with restricted or unreliable data. This potential stems from its capability to explicitly incorporate subjective and uncertain input variables [30]. The primary advantage of FST lies in its ability to introduce a continuum of membership grades and enable a gradual transition between different states. This expansion of traditional Boolean logic from crisp to fuzzy variables enables the incorporation of uncertainties in measurements and observations, leveraging human intuition in the assessment of these uncertainties. [31]. In contrast to crisp sets, which only permit complete membership or non-membership, fuzzy sets facilitate partial membership by assigning degrees within the range of 0 to 1. FST provides flexibility by incorporating linguistic variables, which encompass words and sentences in natural or artificial languages, to estimate probabilities. [32].

2.1.2.1 *Fuzzy Approach Strategy*

In this section, we will utilize the principles of fuzzy sets as a foundation for formulating the multi-criteria decision-making approach using the fuzzy strategy for optimizing natural gas networks with multiple objectives. The statement of this approach is as follows:

A fuzzy set A in the space X = {x, μA(x)} can be defined as the set:

A = {x, MA(x)} ∀ x ϵ X

μ_A: X ⟶ [0, 1]

Where;

$\mu_A(x)$ expressed the grade of membership of x in **A**.

To make a decision, it is necessary to assess all the relevant rules within a knowledge base at various levels. This evaluation process follows the MAX-MIN algorithm [26] and is performed using equation. (1).

$$\boldsymbol{\mu_j(x) = \mathrm{Max}_{i\epsilon I}\{\mathrm{Min}_{N\epsilon N}\{\mu_{i1}(x_1), \mu_{i2}(x_2), \ldots, \mu_{iN}(x_N)\}} \quad (1)$$

Where;

μ_j (x): The membership function of variable x in the fuzzy set corresponds to the rule chosen to be activated at the jth level. $\mu_{iN}(x)$: The membership functions of variable x in fuzzy set.

The MAX-MIN algorithm is executed in two distinct stages:

The MIN operation generates a set of truth values (**λ_i**) by evaluating the membership functions of all the variables in the following manner:

$$\boldsymbol{\lambda_i(x) = \mathrm{Min}.\{\mu_{i1}(x_1), \mu_{i2}(x_2), \ldots, \mu_{iN}(x_N)\}} \quad (2)$$

Next, a single rule is chosen by conducting the MAX operation according to equation (3):

$$\boldsymbol{\lambda = \max.\{\lambda_1, \lambda_2, \ldots\ldots \lambda_i\}} \quad (3)$$

In our multi-objective optimization work, we have two rules are fuzzy quantities represented by fuzzy quantities represented by the following membership functions:

Rule (1): Maximization of gas line pack volume in the network.

$$\mu_1 = \begin{cases} \mathbf{0} & \boldsymbol{f \le fmin} \\ \boldsymbol{\frac{f-fmin}{fmax-fmin}} & \boldsymbol{fmax > f > fmin} \\ \mathbf{1} & \boldsymbol{f \ge fmax} \end{cases} \quad (4)$$

Rule (2): Minimization of power and fuel consumption.

$$\mu_2 = \begin{cases} \mathbf{1} & \boldsymbol{f \le fmin} \\ \boldsymbol{\frac{fmax-f}{fmax-fmin}} & \boldsymbol{fmax > f > fmin} \\ \mathbf{0} & \boldsymbol{f \ge fmax} \end{cases} \quad (5)$$

2.2 Optimization objective functions methodology

2.2.1 *Maximization of the delivered flow rate*

The primary objective of gas pipelines is to transport natural gas to customers, maximizing the amount of gas that can be delivered to consumers under different conditions. This determination considers the operational constraints and client requirements that govern the pipeline system. One possible objective function could be to maximize the flow rate at specific delivery points. [12]. Numerous flow equations have been suggested to depict the correlation between key flow factors and the flow rate within pipes. In this paper, we will utilize equation (6) to describe the panhandle (A) [33].

$$\mathrm{Q} = \mathbf{4.5965} * \mathbf{10^{-3}\left(\frac{T_b}{P_b}\right)^{1.0788}\left(\frac{P_1{}^2-P_2{}^2}{\gamma_g^{0.8539} T_f L Z}\right)^{0.5394} D^{2.6182}} \quad \mathbf{(6)}$$

2.2.2 *Total power and fuel consumption Minimization*

Compressors are utilized to restore high pressure to vast amounts of natural gas that flows over extensive distances within these networks. Along pipelines, stations equipped with natural gas-powered compressors are commonly installed to counteract pressure loss. The compressors consume natural gas as an energy source, leading to an increase in fuel consumption. Enhancing fuel efficiency is crucial when it comes to operating compressor stations. [34], [35]. The power calculation equation (7) can be represented in the following manner: [36]

$$P = ZRT * \frac{Q}{Mw\ gas} * \left(\frac{k}{k-1}\right) * \left(\left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}} - 1\right) \qquad (7)$$

In each compressor, equation (8) is used to calculate the flow rate of gas consumed as fuel during the compression process.

$$m_f = \frac{P_{shaft}}{\eta_i \eta_m \eta_d LHV} \qquad (8)$$

2.2.3 *Line pack maximization*

In pipeline operations, the volume of natural gas during its journey from the compressor's output pressure to the consumer's end-point pressure, where it is ultimately delivered, holds significant significance. Gas pipelines serve a dual purpose; not only do they facilitate the transportation of natural gas from producers to consumers, but they also function as viable storage facilities for maintaining safety stocks, without any plagiarism. [37]. Equation (9) expresses the maximization of the line pack [33].

$$V_b = 7.855 * 10^{-4}\left(\frac{T_b}{P_b}\right) * (\left(\frac{P_{avg}}{Z_{avg}T_{avg}}\right) D^2 L) \qquad (9)$$

2.2.4 *Total cost minimization calculation*

The comprehensive cost model using [38] will be discussed in this section. This total cost will serve as the optimization process's objective function. As shown below, the cost is divided into two parts; the total pipe cost and the total compressor cost.

Total cost= (Investment cost+ operating cost) pipe+ (Investment cost+ operating cost) compressor

2.2.4.1 *Pipe calculations*

- <u>*Pipe investment cost*</u>

The overall investment cost for piping includes both the costs of pipe material and installation. The annual cost, determined using the capital recovery approach outlined in equation (10), is used to calculate the expenses.

$$CIP = (1+R_p)C_p L^l d^m \frac{(1+r)^n r}{(1+r)^n - 1} \qquad (10)$$

- <u>*Pipe operating cost*</u>

Equation (11) establishes that the annual operating cost of the pipeline is anticipated to be directly proportional to the investment cost of the pipe.

$$OC_{pipe} = C_{fp}\frac{(1+r)^n r\,(1+R_p)C_p L^l d^m}{(1+r)^n - 1} \qquad \textbf{(11)}$$

2.2.4.2 *Compressor calculations*

- <u>*Compressor investment cost*</u>

The annual investment cost of the compressor is obtained as follows in equation (12)

$$CIC = C_{hp}\, HP^b \frac{(1+r)^n r}{(1+r)^n - 1} \qquad \textbf{(12)}$$

- <u>*Compressor operating cost*</u>

Compressor operating costs are influenced by various factors, including electricity expenses (if electricity is utilized), maintenance costs, and other expenses associated with the compressor system.

$$O\,C_{comp} = XE_{LC} \qquad \textbf{(13)}$$

$$X = 1 + C_{op} \qquad \textbf{(14)}$$

$$E_{LC} = \frac{1}{8760} P_{Kwh}\, C_e H_y \qquad \textbf{(15)}$$

3 Case Study

Three case studies, based on previous research, have been included in this work, considering variations in their configurations. These case studies encompass linear topology [33], branched topology [34], and cyclic topology [35]. The main goal is to identify the optimal design and objective functions for a specified topology that achieves the desired outcomes.

Natural gas composition and thermodynamic properties are presented in Table (1). Base temperature and pressure are 293 K and 101.13 kPa respectively.

Table (1): Natural gas composition and thermodynamic properties

Component	Mole fraction	Molecular weight	Critical Temperature (K)	Critical Pressure (**kPa**)	Low heating value (MJ/Kg)
Methane	0.85	16.04	190.6	4604.21	50
Ethane	0.1	30.07	305.4	4883.86	47.8
Propane	0.025	44	369.8	4265.78	46.4
Butane	0.025	58	425.1	3796.65	45.8

3.1 Linear Topology Case Study

The initial configuration of a pipeline network is illustrated in Figure (3), which encompasses six nodes including a supply node (node 1) and a demand node (node 6). Each segment within the network has a length of 129 Km. The pressure range spans from 4137 to 6895 Kpa, while the required flow rate for delivery is 17 MMSCMD.

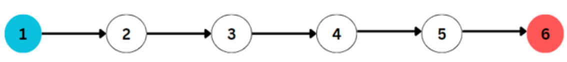

Fig. (3) Linear pipeline configuration

3.2 Branched Topology Case Study

Second configuration of pipeline network is presented in Figure (4) representing the following data: eleven nodes one supply node (node 1) and two demand nodes (node 7, node 11). The pipe consists of 3 branches where the length of branches 1 and 2 is 282 Km while branches 1 and 3 is 322 Km., the pressure range is 1379:6895 Kpa. The input pressure fixed 3447 Kpa at the flow rate required to be delivered is 17 MMSCMD and output pressures was 4137 Kpa and 2068 Kpa respectively for branch 2 and 3.

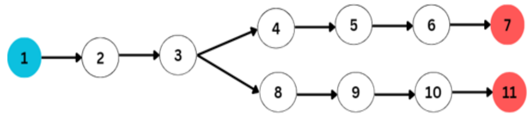

Fig. (4) Branched pipeline configuration

3.3 Cyclic Topology Case Study

The third configuration of pipeline network is presented in Figure (5) representing the following data: nine nodes one supply node (node 1) and two demand nodes (node 8, node 9). The length of each segment is 100 Km, the pressure range is 4137:8274 Kpa. The input pressure fixed 5516 Kpa at the flow rate required to be delivered is 28 MMSCMD and the output pressures was 4482 Kpa for each demand node.

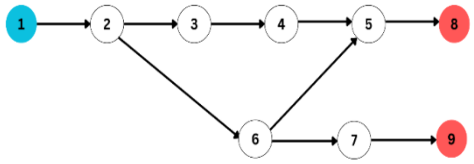

Fig. (5) Cyclic pipeline configuration

4 Results and discussion

4.1 Optimization for Linear Topology

By the utilization of GAMS as shown in table (2), we effectively ascertained the optimal number of compressors and their precise placements for different diameters. This determination was achieved by employing fuzzy logic and taking into account the calculations of main objective functions, including line pack, fuel consumption, and power consumption as shown in table (3). Through the integration of these scientific methodologies, we successfully identified the configuration that offers the highest level of efficiency as shown in figure (6).

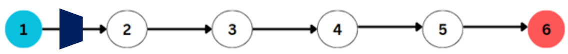

Fig. (6) Optimum linear configuration

Table (2): The results of linear topology through GAMS.

Try	Diameter (mm)	Number of compressors	Power (Kw)	Line pack (MMCM)	Fuel consumption (Kg/s)
1	914.4	1	8724	15.87	5.98
2	863.6	2	10580	15.06	7.25
3	812.8	3	13340	13.84	9.147
4	762	4	18260	12.38	12.5
5	711.2	5	27275	10.77	18.702
Min	-	-	8724	10.77	5.98
Max	-	-	27275	15.87	18.702

The **normalization** value of each objective function by using Min-Max fuzzy are presented in **table (3)** where the minimum value of each raw is shown in **yellow** while the maximum of the minimum values is shown in **Blue.**

Table (3): normalization values by using Min-Max fuzzy.

The cost for each scenario was computed by applying equations (10:13) to evaluate various diameters. The objective was to identify the diameter that would result in the lowest cost while meeting the desired objective functions. After conducting thorough calculations, it was determined that the minimum cost coincides with the optimum diameter, successfully fulfilling the desired objectives. The main results is illustrated in table (4). The final optimum results are diameter (36") and the least cost is (292.15 M$/year).

Diameter (mm/inch)	Power	Line pack	Fuel consumption	Min	Max
914.4 (36")	1	1	1	1	1
863.6 (34")	0.89	0.84	0.90	0.84	
812.8 (32")	0.75	0.60	0.75	0.60	
762 (30")	0.48	0.31	0.48	0.31	
711.2 (28")	0	0	0	0	

Table (4) Relation between the diameter and the cost

Try	Diameter (mm)	Number of compressors	Cost (M$/yr.)
1	914.4	1	292.15
2	863.6	2	324.45
3	812.8	3	363.69
4	762	4	455.64
5	711.2	5	675.28

4.2 Optimization for Branched Topology

By employing GAMS, as depicted in Table (5), we effectively determined the optimal quantity of compressors and their precise locations for different diameters. This achievement was made possible through the application of fuzzy logic and the consideration of essential objective functions such as line pack, fuel consumption, and power consumption, as demonstrated in Table (5). Through the integration of these scientific methodologies, we successfully identified the configuration that maximizes efficiency to the highest degree, as illustrated in Figure (7).

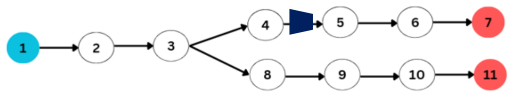

Fig. (7) Optimum Branched configuration

Table (5): The results of branched topology through GAMS.

Try	Diameter (mm)	Number of compressors	Power (kW)	Line pack (MMCM)	Fuel consumption (Kg/s)
1	914.4	1	3443	8.44	2.24
2	863.6	1	3125	8.45	2.19
3	812.8	1	2717	8.54	1.9
4	762	2	8157	7.7	5.48
5	711.2	3	13894	7.83	9.7
Min	-	-	**2717**	**7.7**	**1.9**
Max	-	-	**13894**	**8.54**	**5.48**

The **normalization** value of each objective function by using Min-Max fuzzy are presented in **table (6)** where the minimum value of each raw is shown in **yellow** while the maximum of the minimum values is shown in **Blue.**

Table (6): normalization values by using Min-Max fuzzy.

Diameter (mm)	Power	Line pack	Fuel consumption	Min	Max
914.4	0.93	0.88	0.95	0.88	
863.6	0.96	0.89	0.96	0.89	
812.8	1	1	1	1	
762	0.51	0	0.54	0	
711.2	0	0.15	0	0	

The cost for each scenario was computed by applying equations (10:13) to evaluate various diameters. The objective was to identify the diameter that would result in the lowest cost while meeting the desired objective functions. After conducting thorough calculations, it was determined that the minimum cost coincides with the optimum diameter, successfully fulfilling the desired objectives. The main results is illustrated in table (7). The final optimum results are diameter (36") and the least cost is (78.13 M$/yr).

Table (7) relation between the diameter and the cost

Try	Diameter (mm)	Number of compressors	Cost (M$/yr.)
1	**914.4**	**2**	**327.07**
2	863.6	2	446.93
3	812.8	3	652.20
4	762	5	817.64
5	711.2	5	940.85

4.3 Optimization for cyclic Topology

By employing GAMS, as depicted in Table (8), we effectively determined the optimal quantity of compressors and their precise locations for different diameters. This achievement was made possible through the application of fuzzy logic and the consideration of essential objective functions such as line pack, fuel consumption, and power consumption, as demonstrated in Table (9). Through the integration of these scientific methodologies, we successfully identified the configuration that maximizes efficiency to the highest degree, as illustrated in Figure (8).

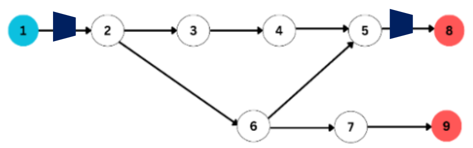

Fig. (8) Optimum Cyclic configuration

Table (8): The results of cyclic topology through GAMS.

Try	Diameter (mm)	Number of compressors	Power (kW)	Line pack (MMCM)	Fuel consumption (Kg/s)
1	914.4	2	9900	33.17	6.788
2	863.6	2	13458	30.7	9.22
3	812.8	3	19532	27.06	12.79
4	762	5	25908	22.96	17.65
5	711.2	5	29320	20.93	20.1
Min	**-**	**-**	**9900**	**20.93**	**6.788**
Max	**-**	**-**	**29320**	**33.17**	**20.1**

The **normalization** value of each objective function by using Min-Max fuzzy are presented in **table (9)** where the minimum value of each raw is shown in **yellow** while the maximum of the minimum values is shown in **Blue**

Table (9): normalization values by using Min-Max fuzzy.

Diameter (mm)	Power	Line pack	Fuel consumption	Min	Max
914.4	1	1	1	**1**	**1**
863.6	0.98	0.80	0.81	**0.80**	
812.8	0	0.5	0.55	**0**	
762	0.91	0.17	0.18	**0.17**	
711.2	0.90	0	0	**0**	

The cost for each scenario was computed by applying equations (10:13) to evaluate various diameters. The objective was to identify the diameter that would result in the lowest cost while meeting the desired objective functions. After conducting thorough calculations, it was determined that the minimum cost coincides with the optimum diameter, successfully fulfilling the desired objectives. The results is shown in table (10). The final optimum results are diameter (36") and the least cost is (327 M$/yr).

Table (10) relation between the diameter and the cost

Try	Diameter (mm)	Number of compressors	Cost (M$/yr.)
1	914.4	1	102.46
2	863.6	1	91.23
3	**812.8**	**1**	**78.13**
4	762	2	202.46
5	711.2	3	346.66

The research findings emphasize the effectiveness of optimized models in determining the optimal objective function for natural gas pipeline networks. This, in turn, leads to cost reduction across the network. The results highlight the models' ability to select the most suitable criteria, resulting in a more efficient and cost-effective operation. In linear topology, where the flow rate was 17 MMSCMD and the pipe diameter was 36 inches, the total cost was reduced to $292 million per year. This demonstrates the successful identification of a cost-effective solution for this specific network configuration. Similarly, in the branched topology case study with the same flow rate, a pipe diameter of 32 inches was determined as optimal, resulting in a total cost of $78 million per year. This showcases the adaptability of the optimization process to different network topologies. In the cyclic topology case study with a flow rate of 28 MMSCMD, a pipe diameter of 36 inches was found to be optimal, leading to a total cost of $327 million per year. This further supports the effectiveness of the optimization process in minimizing costs for various network configurations. The research paper highlights the importance of utilizing mathematical modelling techniques to optimize the transmission networks of natural gas pipelines.

By taking into account specific constraints and objectives, these optimized models have the potential to substantially decrease costs while ensuring the efficient and dependable transportation of natural gas. Figure (9) presents a comparative analysis of compressor power requirements across the three case studies. The graph distinctly showcases that the branched topology, characterized by its shorter length, necessitates the least amount of power, especially when operating at a flow rate of 17 MMSCMD. In contrast, the cyclic topology, responsible for transmitting a higher flow rate of 28 MMSCMD over a longer distance, exhibits the highest power demand. This observation underscores the direct correlation between topology, flow rate, pipeline length, and the associated power requirements in natural gas transmission networks.

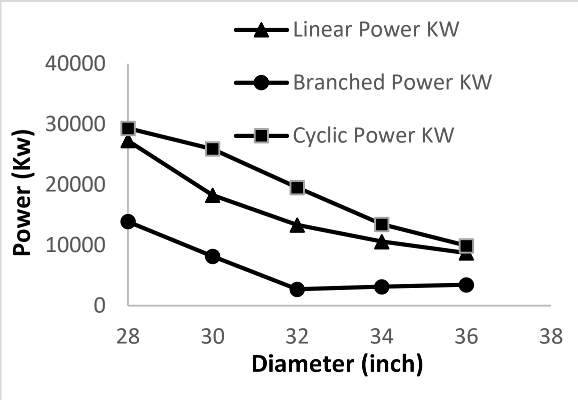

Fig. (9) Comparison of compressor power

The analysis of Table (11) reveals a direct relationship between pipeline length and associated costs. As the pipeline length increases, costs rise due to factors such as material requirements, construction expenses, and maintenance needs. Considering pipeline length is crucial for project feasibility evaluation and cost estimation.

However, it is important to investigate deeper into the discrepancy observed between the first and third cases. Apart from pipeline length, topology, and flow rate also significantly impact overall costs. In the third case with a cyclic topology, the configuration is more complex compared to the linear and branched topologies of the first two cases. This complexity necessitates a higher number of compressors to maintain the desired flow rate and pressure levels throughout the pipeline network. As compressors are costly to install, operate, and maintain, the increased number of compressors in the cyclic topology contributes to its higher cost. Additionally, the flow rate of the pipeline plays a crucial role in determining costs. Higher flow rates require more robust infrastructure, larger pipe diameters, and additional compressors to maintain desired pressure levels. Consequently, the cyclic topology with its complex configuration and higher flow rate requires a greater number of compressors, resulting in a significantly higher overall cost compared to the other cases, as shown in Figure (10)

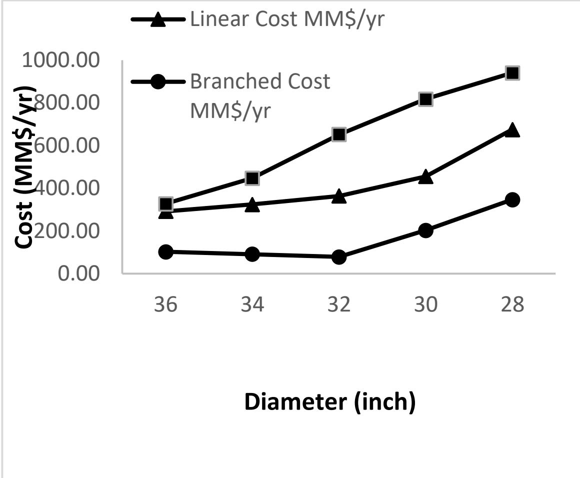

Fig. (10) Total cost comparison of each case study

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Table (11) Final results

Cases	Diameter D (mm/inch)	Flow rate Q (MMSCMD)	Length L (Km)	Pressure range P (Kpa)	Power P (Kw)	Line pack V_b (MMCM)	Fuel consumption m_f (Kg/s)	Number of compressors	Cost (M$/yr)
Linear topology	914.4/36	17	774	4137:6895	8724	15.87	5.98	1	292
Branched topology	812.8/32	17	322	1379:6895	2717	8.54	1.9	1	78.12
Cyclic topology	914.4/36	28	500	4137:8274	9900	33.17	6.788	2	327

5 Conclusion and future work

This research paper explores the cost-effectiveness of natural gas transmission through pipeline networks using an innovative approach that combines the General Algebraic Modeling System (GAMS) and fuzzy multi-criteria decision analysis (FMCDA). Three case studies with different network topologies (linear, branch, and cyclic) are conducted. The optimized models successfully determine the optimal objective function, including maximizing line pack, minimizing compressor power, and reducing fuel consumption, resulting in cost reduction for each scenario. The findings indicate a positive correlation between pipeline length and overall costs, with variations observed among topologies and flow rates. The proposed approach enables the evaluation of different pipeline scenarios and the assessment of changes in pipeline length and pressure differentials. For example, in a linear topology with a flow rate of 17 MMSCMD and an optimal pipe diameter of 36 inches, the total cost was reduced to $292 million per year. Similarly, the branched topology, with the same flow rate but a shorter length, required less power, leading to a cost reduction of $78 million per year. Conversely, the cyclic topology, with a higher flow rate of 28 MMSCMD, required more power, resulting in a total cost of $327 million per year.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Abbreviations

GAMS	**General Algebraic Modelling system**
FMCDA	Fuzzy Multi-Criteria Decision Analysis
MMCM	Million cubic meters
MMSCMD	Million standard cubic meter per day
MCDM	Multi-Criteria Decision Making
FST	Fuzzy Set Theory
MINLP	Mixed integral Non-linear programming

Nomenclature

Parameter	*Identification*	*Unit*
γ_g	Gas specific gravity	-
T_b	Base temperature	K
P_b	Base pressure	Kpa
P_1	upstream pressure	Kpa
P_2	downstream pressure	Kpa
T_f	Flow temperature	K
T_{avg}	The average temperature of gas	K
P_{avg}	The average pressure of gas	Kpa
L	Pipe length	Km
D	Pipe diameter	mm
K	Specific heat ratio (Cp/Cv) is assumed to be 1.26	-
R	Universal gas constant	KJ/Kmol K
Mw_{gas}	Gas molecular weight	-
Z	Gas compressibility factor	-
LHV_i	Individual lower heating value	KJ/Kg
LHV	lower heating value of gas mixture	KJ/Kg
Q	Gas flow rate	Kg/s
P	The power required for compression process	Kw
m_f	is the mass flow rate of consumed gas as fuel for the compressor	Kg/s
η_m	Is the mechanical efficiency of compressor “0.9”	-
η_d	the driver efficiency of compressor “0.75:	-
η_i	Isentropic efficiency “0.8”	-
V_b	Line pack	MMCM
CIP	Pipe investment cost	$/ year
r	Annual interest rate “12%”	-
Cp	Cost for a pipe/ diameter/ length “0.569”	$/in/ft
n	Life time of pipeline “20”	years
l,m,b	Non linearity constant obtained from regression “1, 1.428, 1.465”	-
CIC	Compressor investment cost	$/ year
C_{hp}	Compressor cost/ horse power “2000”	$/ hp
OC_{pipe}	Pipe operating cost	$/ year
C_{fp}	Fraction ratio of pipe operation cost to maintenance “0.2” (yearly maintenance cost)	-
OC_{comp}	compressor operating cost	$/ year
x	Is assumed to be 1.75	-
C_e	Electricity cost “0.055”	$/Kwh
H_y	Operating time “8760”	Hours

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