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TECHNO-ECONOMIC OPTIMISATION OF GAS COMPRESSOR STATION LOCATION AS A DECISION VARIABLE

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ABSTRACT

An economical natural gas transportation will require the lowest possible capital and operating expenditures over its lifecycle. To attain these conditions, the designers and investors must estimate the number of compressor stations (CS) that are needed along the pipeline route. More so is the need to determine their optimised locations at various pipeline segments along the pipeline. This study considers the techno-economic optimisation of the compressor station and pipeline segments, making up the proposed Trans-Saharan Gas Pipeline (TSGP) project. The optimised lifecycle cost, CS locations and pipeline segments are evaluated with the main aim of minimising costs. A SIMULINK model is developed using the techno-economic and environmental risk analysis (TERA) framework. The model is incorporated with an optimiser that enables an economic analysis of the TERA framework. Including the optimiser affects the outcome of the TERA in terms of the lifecycle cost. The optimisation problems are formulated considering the compressor station location as the decision variable. The lifecycle cost of the compressor stations and pipeline system is the objective function. A scenarios-based techno-economic optimisation study is performed to mimic the standard compressor station and pipeline system network configurations in the real world. The baseline case consists of 18 compressor stations at fixed locations along the pipeline route.

The results show 12 compressor station locations along the pipeline route with a reduction in the lifecycle cost by 12.95% in one of the optimised scenarios compared to the baseline case. The net present value is $28.77 billion assuming a discount rate of 15%. The optimised compressor station locations are at 1, 38, 76, 113, 150, 186, 222, 260, 296, 332, 368, and 408 segments of the pipeline. The outcome of the analyses shows the importance of the two-level optimisation algorithm utilised by the SIMULINK model for the integrated TERA. Hence, this study shows the potential of the TERA modelling and CS location optimisation method utilised in this research in guiding decision-makers on the selection of compressor-turbine configurations. These configurations will give the optimal lifecycle cost at the optimised compressor station locations along the pipeline route.

Keywords: Lifecycle cost, SIMULINK, Genetic Algorithm, TERA, Trans-Saharan Gas Pipeline, Objective function, Constraint

NOMENCLATURE

C	Pipe material cost, $/metric ton
CS	Compressor station
D	Pipeline diameter, mm
E	Pipeline efficiency
F_c	Compressor correction factor
F_{lc}	Fuel consumption cost, $
G	Gas gravity
GC	Gas compressor
GC_c	Gas compressor cost, $
GT	Gas turbine
GT_c	Gas turbine cost, $
GUI	Graphical user interface
H_1	Upstream elevation, m
H_2	Downstream elevation, m
L	Station location, pipe length, km
L_c	Lifecycle cost, $
L_e	Pipeline equivalent length, km
L_n	Optimised compressor station location, km
m	Mass flow rate, kg/s
M	Marshall & Swift cost index

M_{lc}	Maintenance cost, $
MAOP	Maximum allowable operating pressure
n	Polytropic exponent
N	Number
η_p	Polytropic efficiency
Nos	Numbers
P_1	Pipe inlet pressure, GC discharge pressure, kPa
P_2	Pipe outlet pressure, GC suction pressure, kPa
P_{aux}	Auxiliaries cost, $
P_b	Base pressure, kPa
P_{c_w}	Pipe coatings and wrapping cost, $/km
P_G, P_{GC}	Gas compressor power, kW
P_i	Pipeline initial project cost, $
P_t	Pipeline cost, $
P_T	Gas turbine power, kW
PIPC	Pipeline initial project cost, $
Q	Volumetric flowrate, m^3/day
R	Gas constant, KJ kg^{-1} K^{-1}
s	Elevation adjustment parameter
T	Pipe wall thickness, mm
T_b	Base temperature, K
TERA	Techno-economic environmental risk analysis
TET	Turbine entry temperature, K
T_f	Gas flow temperature, K
TSGP	Trans-Saharan gas pipeline
x	Outer diameter
y	Pipeline installation cost, $/km
Z	Compressibility factor

1. INTRODUCTION

Natural gas has wide use in the power generation and transportation industries including being used for residential cooking and heating. This is usually due to its low emission and environmental pollution in comparison to other fossil fuels, particularly coal. Natural gas share in global primary energy demand continues to increase, accounting for 24.7% in 2020 [1]. It has been reported that Europe consumed more natural gas than it produced [2]. The difference between its natural gas consumption and production is usually imported from other countries with sufficient supplies. Thus, it is understood that natural gas demand in Europe is anticipated to rise in the coming years [3, 4] despite the present emphasis on renewable energy and the desire to achieve net zero by 2050. Therefore, a viable scheme needs to be accomplished to improve natural gas supply to Europe and other locations with increased demand. The proposed Trans-Saharan Gas Pipeline (TSGP) project is anticipated to improve natural gas supply. The 4180 km hypothetical natural gas pipeline would carry natural gas from Nigeria to the Algerian coast and eventually supply natural gas to Europe [5, 6]. The TSGP is anticipated to minimise gas flaring and contribute to the World Bank's target of zero routine flaring by 2030 [1].

There are various methods of transporting natural gas from the production source location to areas with increasing demands. These methods include Liquefied Natural Gas, Compressed Natural Gas, Pipelines, Gas to Liquid, Gas to Wire, Gas to Commodity, and Gas to Solids [7, 8]. Moreover, pipeline networks or tankers in the form of Liquefied Natural Gas are a more suitable method of transporting natural gas over long distances [9, 10]. Natural gas transportation via pipelines has been recognised as one of the most efficient and cost-saving methods of transportation to areas with increasing demands for natural gas [11-15]. Nonetheless, the European gas market gas-on-gas competition has taken the form of pipeline imports competing against Liquefied Natural Gas imports [16, 17]. The world trade movement by pipeline accounted for 60.8% in 2020. This percentage represents about 755.8 billion cubic meters of natural gas transportation in pipelines [1]. Natural gas transmission pipelines serve as links between the gas source and the consumers. Therefore, the efficient operation of each component of the transmission pipeline is important. The transmission pipelines range from 10 to 56 inches in diameter [18, 19] and the selection of suitable pipe size will depend on their particular application. These transmission pipelines are used for long-distance gas transportation and are usually made of carbon steel. This ensures it can endure the high pressure associated with gas transportation in this type of pipeline. More so, these pipelines will require that compressor stations be installed at specified distances along the pipeline. This will ensure that the pressure does not drop beyond the allowable operating pressure of the pipeline [1]. In this case, the required limit could be the required delivery pressure of the pipeline. Figure 1 shows a typical natural gas transmission pipeline system schematic diagram. It shows compressor stations and transmission pipelines as the main components.

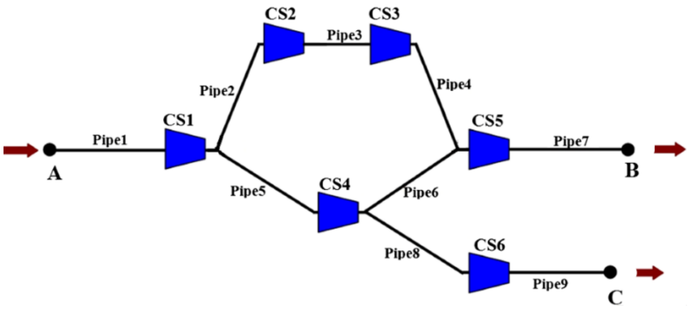

FIGURE 1: TYPICAL NATURAL GAS TRANSMISSION SYSTEM LAYOUT [20]

With the demand for natural gas, compressor stations are needed for the transportation of natural gas via pipelines from the production source to the delivery point. In the present study, compressor station location refers to the geographical location of the transmission pipeline influencing elevation and ambient conditions. According to Menon [21], compressor station location and operating pressures are controlled by the drivers and driven power, maximum allowable pipe pressures, environmental and geotechnical factors. Compressor stations are usually installed at various locations on the natural gas transmission pipelines. This will ensure that the pressure needed for gas transportation is maintained. Prime movers as mechanical drivers are needed for these compressor stations for efficient operation. Zhang et al. [22] itemize choices from three types of drivers: gas turbines, reciprocating gas engines, and electric motors. Nevertheless, the final decision on driver selection will depend on the economics or existing regulations of the countries where the compressor station is located. Nasir [19] studied the techno-economics of the gas turbine or electric motor drives as prime movers in pipelines. His study concluded that electric motor drives might initially seem better in terms of environmental pollution. However, considering the power generation aspect of electricity supplied for electric motor drivers today and in the future, these contribute more to environmental pollution than gas turbines. It may not be a feasible option for the interstate pipeline in locations with inadequate electricity supply. This study employed gas turbine engines as the promising prime mover option.

There are very few studies on the TERA approach for gas turbine application in natural gas transmission pipeline systems. The known work done on this area of research was performed by Nasir [19], Tukur [23], and Aziaka [24] at Cranfield University, United Kingdom. A closely related work was done by El-Suleiman [25]. He investigated TERA on carbon dioxide compression power requirements for gas turbine-driven pumps and compressors. The economic model was developed based on net present value. However, the study did not consider natural gas pipelines. Tukur [23] investigated the techno-economics of gas turbine compressor stations in natural gas pipelines. His economic model was performed based on the lifecycle cost by assuming constant annual values for maintenance and fuel cost and considering station local conditions. Aziaka [24] investigated the techno-economics of degraded gas turbines on pipeline applications in given compressor station locations. Nevertheless, these studies did not consider an optimisation analysis using compressor station location as a decision variable.

Lifecycle cost analysis is an approach used to evaluate the economic performance of projects throughout their lifecycle. The lifecycle cost of the transmission pipeline network system is mainly dependent on the compressor station operating cost. Some studies in the literature have evaluated economic models for various drivers and driven equipment in gas compression applications in natural gas transmission pipelines to minimise the total investment cost [26–28]. According to [12], and [29], the compressor station operating cost could represent between 25% and 50% of the total company's operating budget. Nonetheless, the operating cost of the compressor station and pipeline system could account for values exceeding 50% to 85% of the total company's operating budget. Therefore, a slight improvement of the compressor station and pipeline system lifecycle cost through an optimisation study could bring about huge benefits.

A vast volume of work has been done over the preceding years on transmission pipeline network optimisation. Recently, there has been an increase in natural gas pipeline optimisation parameters and techniques to obtain maximum compressor station and pipeline operational benefits [30]. Zhang et al. [22] examined the important considerations for new pipeline design and existing pipeline expansion that include lifecycle cost and optimisation technologies. They concluded that the balance between maximum allowable operating pressure, pressure ratio, pipe diameter, total horsepower, and number of compressor stations for a specified distance is important in reducing the initial capital cost of a new pipeline project. Uster and Dilaveroglu [4] present an optimisation problem for the design or expansion of natural gas transmission networks based on an integrated large-scale mixed-integer non-linear optimization model to minimize investment and operating costs. Rios-Mercado and Borraz-Sanchez [29] presented a review of the relevant research work performed on the optimization of natural gas transportation systems, especially natural gas transmission networks. They discussed both steady-state and transient optimisation models while assuming an existing pipeline network to minimise the operational cost.

Marcoulaki et al. [31] have presented a stochastic optimisation framework for designing pipeline systems intended for fluid transmission that includes natural gas. The approach proposes a systematic search for optimal solutions using the same information and simulation tools with respect to design by trial-and-error analysis. Optimisation technologies are integrated with geographical information, process simulators, and equipment databases. They illustrate their proposed approach to designing a pipeline traversing mountainous terrain. They concluded that the use of different geographical data influences pipeline investment and calls for different optimal pipeline designs. Sanaye and Mahmoudimehr [32] proposed an optimisation program for the design of a natural gas transmission network which considers different design parameters. These include network layout, pipe diameters, supply and delivery pressures, number, and locations of compressor stations. They employed pipeline size, adjacent matrix of network, and pressure at each supply or delivery node as decision variables. The optimal values of the remaining design parameters were determined based on the optimal properties of single pipelines. The result obtained through the optimisation process for their case study yields about 1.45% savings in total cost. However, these studies do not examine a techno-economic analysis using the compressor station location as a decision variable. The authors could not find any literature that looks at the techno-economic optimisation of compressor stations and pipeline systems using station location as a decision variable. Therefore, there exists a knowledge gap in the literature that this study intends to accomplish. For the first time, this study performed a techno-economic optimisation of gas compressor station location as a decision variable. The optimisation considers the impact of ambient conditions and altitude on the lifecycle cost. Therefore, it considers topographical data.

While preceding studies looked at this transmission pipeline network optimisation problem using various approaches. A techno-economic optimisation of the compressor station and pipeline system using compressor station location as the decision variable is proposed in this study. This techno-economic optimisation study is based on the TERA framework. Furthermore, it can determine the optimal locations of the compressor stations while optimising for the lowest lifecycle cost. As evident from the information available in the public domain, this is the first time that such an optimisation study has been done on the transmission pipeline from a techno-economic perspective.

For the first time, this study looks at the following:

- How many compressor stations are needed along the pipeline routes based on the TERA approach?
- Where are the optimised locations of each compressor station along the pipelines? Also, what pipeline segments are the optimised compressor station locations?
- What is the optimised lifecycle cost for different considered scenarios?
- Which optimised turbo-compressor configurations have the lowest lifecycle cost and highest net present value?

The remaining section of this paper is organised as follows. In section 2, the methodology for the techno-economic optimisation analysis using the compressor station location as the decision variable is described. The different modules that make up the TERA framework are presented. More so, the approaches used by the optimiser for the techno-economic optimisation study are discussed. Additionally, the SIMULINK optimisation procedure is described. Subsequently, the optimisation problem is formulated. Finally, the decision variable, constraint, and the objective function are identified. Results as the outcome of the techno-economic optimisation study are presented and discussed in section 3. Conclusions and recommendations for future studies are made in section 4.

2. METHODOLOGY

This section describes the methods utilised for the techno-economic optimisation analysis using the compressor station location as the decision variable. In particular, the method of approach employed by the optimiser for the techno-economic optimisation study is explained.

Figure 2 shows the TERA framework for natural gas pipeline application utilised in this study with its key analysis modules. As depicted in the figure, the entire computation is initiated by compressor station location which depends on the local conditions at each station.

The pipeline module models the proposed TSGP's pipeline parameters and simulates the pressure drop along the pipeline. The gas compressor module estimates the gas compressor drive power requirement at design and off-design conditions needed to supply the required throughput through a specified pressure ratio. The gas turbine performance module simulates the design and off-design performance of the selected gas turbine. The engine performance model was done using TURBOMATCH, an in-house software developed at Cranfield University. The maintenance module shows the effects of the maintenance schedule on engine availability as a function of the local condition. The availability module estimates the percentage of time the engine is available to generate power in each period as a function of downtime. It evaluates the turbo-compressor availability needed for the availability-based maintenance cost computation. The economic module estimates the techno-economic lifecycle costs arising from the integrated TERA framework.

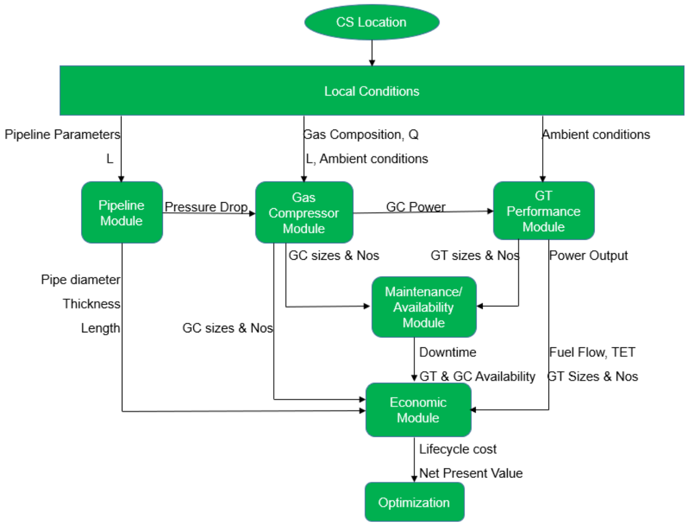

FIGURE 2: The TERA FRAMEWORK USING STATION LOCATION AS A DECISION VARIABLE

The techno-economic model was carried out using SIMULINK which integrates the complete TERA framework. The developed model is employed by the optimisation scheme to determine the Trans-Saharan gas pipeline project lifecycle cost. The model comprises the following subsystems according to the TERA framework: pipeline subsystem, gas compressor subsystem, pipeline cost subsystem, gas compressor cost subsystem, gas turbine subsystem, gas turbine cost subsystem, and auxiliaries cost subsystem. Each subsystem is connected successively including the blocks for the fuel and maintenance costs according to the TERA framework to make up the complete SIMULINK model.

The pipeline subsystem is modelled based on the Weymouth gas flow equation. Equation (1) below gives downstream pressure:

$$P_2 = \left[\left({P_1}^2 - \frac{7.136\times10^4 Q^2 {P_b}^2 G T_f L_e Z}{{T_b}^2 E^2 D^{5.334}}\right)\exp(-s)\right]^{0.5} \quad (1)$$

Where L_e is the equivalent length which considers the variation in elevation between the ends of each pipe segment and is given by:

$$L_e = \frac{L(e^s - 1)}{s} \quad (2)$$

The elevation adjustment parameter s, is given as:

$$s = 6.84 \times 10^{-2} G \left(\frac{H_2 - H_1}{T_f Z} \right) \tag{3}$$

The gas compressor subsystem is modelled using Equation (4). The power required by the gas compressor is given below:

$$P_{GC} = \frac{2.778 \times 10^{-4} m Z_{avg} R T_f \frac{n}{n-1} \left[\left(\frac{P_2}{P_1} \right)^{\frac{-(n-1)}{n}} - 1 \right]}{\eta_p} \tag{4}$$

Equation (5) below gives the pipeline cost:

$$P_t = 2.46 \times 10^{-2} (D - T) TLC + (y + P_{c\_w}) L \tag{5}$$

Where y is the installation cost in $ per km and is given by:

$$y = 2.13 \times 10^2 x^2 + 1.29 \times 10^3 x + 1.06 \times 10^5 \tag{6}$$

The gas compressor cost is modelled using Equation (7) [1, 35, 36]:

$$GC_c = 1.453 M \left(P_{GC}{}^{0.82} \right) (2.11 + 2F_c) \tag{7}$$

Where M is the Marshall and Swift cost index, equivalent to 1638.2 for 2018 [37].
The gas turbine cost is modelled using the following equation [1, 38]:

$$GT_c = 2.44 \times 10^4 N \left(P_T{}^{-0.294} \right) \tag{8}$$

The auxiliaries' cost is given by [1]:

$$P_{aux} = 0.435 P_i \tag{9}$$

Where P_i is the pipeline initial project cost equivalent to the project investment cost and is given by Equation (10).

$$P_i = P_t + GC_c + GT_c \tag{10}$$

Figure 3 shows the developed SIMULINK model of the TERA framework using SIMULINK block diagrams.

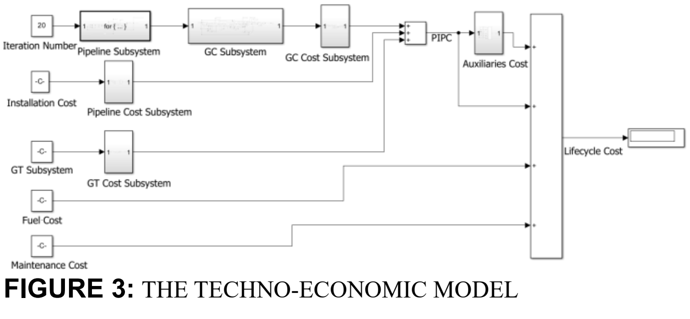

FIGURE 3: THE TECHNO-ECONOMIC MODEL

The number of iterations is the input to the pipeline subsystem. The pipeline subsystem is the input to the SIMULINK model. The output from the pipeline subsystem is the input to the gas compressor subsystem. The output from the gas compressor subsystem is the input to the gas compressor cost subsystem. The sum of the outputs from the gas compressor cost, gas turbine cost, and pipeline cost subsystems gives the pipeline's initial project cost (PIPC). The output from the PIPC is the input to the auxiliaries cost subsystem. The sum of the outputs from the PIPC, auxiliaries cost subsystem, fuel and maintenance blocks yields the lifecycle cost for the compressor station and pipeline system. This lifecycle cost estimate depends on the location's ambient temperature.

2.1 TERA Optimisation Approach

Techno-economic optimisation study is performed on varying compressor station configurations of gas turbines and gas compressors based on four scenarios:

i. Scenario 1: Four 15 MW capacity units of installed simple cycle three shafts aero-derivative gas turbine driving four units of gas compressors arranged in parallel at each compressor station location.
ii. Scenario 2: Three 30.1 MW capacity units of installed simple cycle two shafts gas turbine driving three units of gas compressors arranged in parallel at each compressor station location.
iii. Scenario 3: Two 50 MW capacity units of installed simple cycle two shafts gas turbine driving two units of gas compressors arranged in parallel at each compressor station location.
iv. Scenario 4: One 117 MW capacity unit of installed inter-cooled aero-derivative gas turbine drives one gas compressor unit at each compressor station location.

An economic analysis using the compressor station location as the decision variable is performed. The maximum allowable pipe pressure which is a function of the power required is the constraint. The compressor station and pipeline system's lifecycle cost is the objective function. More so, the main aim is to maximise profit through decision-making on the best project scenario. The TERA optimisation was carried out using SIMULINK block diagrams and the response optimisation tool available in MATLAB SIMULINK graphical user interface (GUI). The SIMULINK optimisation tool utilises a gradient descent optimisation technique with a sequential quadratic programming algorithm to compute the objective function values of the decision variables. The results are compared with the genetic algorithm optimisation method available in the MATLAB toolbox. The genetic algorithm is a population-based optimization method that is based on the principles of genetics and natural selection. A detailed discussion of genetic algorithm optimization technique is not given in this paper due to the scope of this study.

2.1.1 Optimisation Assumptions

A location identification system is incorporated into the optimisation scheme. This identification system allows the optimiser to use the compressor station location as a decision variable. This was connected to the distance from the source of the natural gas that is being transported. Therefore, the source is at a location point of 0 km and the natural gas delivery location point is at 4180 km from the source. The whole natural gas pipeline was divided into pipe segments. The source compressor station is in pipe segment 1, which represents the 0-9 km length of the complete natural gas pipeline. Each natural gas pipeline segment is 10 km long. Pipeline segment 'n' is '10(n) – 10' to '10(n) – 1' km in length. The outcome of the optimisation algorithm is a sequence of numbers at the optimised compressor station locations along the natural gas pipeline route. Consequently, such an arrangement yields an automatic compressor station position and adequate resolution for the optimisation analysis.

The following shows the assumptions used in the optimisation analysis:

a. The natural gas pipeline distance of 4180 km is the same for all scenarios
b. The maximum allowable operating pressure of the pipeline is 10000 kPa
c. The project lifecycle is 30 years
d. Pipeline configuration is the same as the baseline case
e. The discount rate is 15 %

2.1.2 SIMULINK Optimisation Procedures

Figure 4 shows the SIMULINK optimisation flowchart utilised in this study. The SIMULINK optimisation process is started by defining the initial values of the decision variable in the MATLAB command window. A new set of the decision variables to be optimised is generated in SIMULINK by defining the decision variable's initial, minimum, and maximum values including the scaling factor if necessary. The decision variable changes values during the optimisation process, these can be seen in the design optimisation workspace. Subsequently, the constraint requirements are defined by specifying them on the GUI. More so, the model signal to be logged for evaluation against the constraint requirements is specified. In this study, the model signal is the objective function in the form of the project lifecycle cost. Thereafter, the signal bound is selected from the SIMULINK GUI. The constraint on the gas compressor power which depends on the pipeline's maximum allowable operating pressure of 10,000 kPa is specified. The custom requirement is created by calling the MATLAB function that specifies this custom requirement. The minimum requirement type is selected because the objective function which in the present study is the project lifecycle cost for the imposed gas compressor power requirement is being minimised. Thus, the MATLAB function subsequently processes the structured data containing the decision variables being optimised and the model signal in the form of an objective function.

Furthermore, the SIMULINK optimisation methods are selected. The SIMULINK optimisation approach utilises a two-level optimisation method to analyse the techno-economic model. A gradient descent optimisation method with a sequential quadratic programming algorithm is selected. This method is selected because of its computational efficiency and its ability to produce stable convergence. The gradient descent optimisation method is a robust optimisation method that uses a first-order iteration method to find the local minimum of the objective function [33]. More so, the sequential quadratic programming algorithm converts the nonlinear optimisation problem into a sequence of quadratic programming sub-problems [34]. The optimisation process is easy to implement due to fewer iterations and the speed at which convergence is attained.

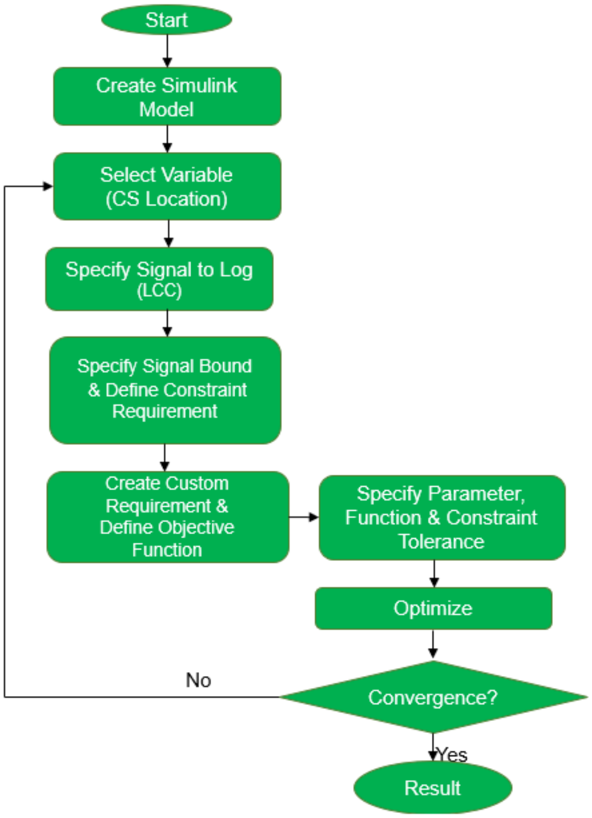

FIGURE 4: FLOWCHART OF THE SIMULINK OPTIMISATION APPROACH

2.1.3 Formulation of the Optimisation Problem

The optimisation problem is formulated with the main aim of optimising the compressor station and pipeline system's project lifecycle cost. This considers the compressor station location as the decision variable. The baseline case is made up of eighteen compressor stations at fixed locations along the pipeline route. Four gas turbine models are selected for this base case. These are inspired by double-shafts industrial gas turbine of 13.4 MW capacity, 19.3 MW triple-shafts industrial gas turbine, 15.2 MW and 17 MW triple-shafts aeroderivative gas turbines respectively. Four identical gas compressors arranged in parallel are selected. Each gas compressor is connected in series with the selected gas turbine. Details on the selected compressor-turbine configuration for the baseline case are outside the scope of this study. The techno-economic study looks at four scenarios as described in section 2.1.

The optimisation scheme includes the gas compressor and gas turbine performance modules, the availability module, and the economic module. The gas compressor and gas turbine performance modules estimate the gas compressor power requirement and the gas turbine power that matches the gas compressor power based on the fuel consumption and turbine entry temperature. The availability module evaluates the turbo-compressor availability needed for the availability-based maintenance cost computation. The economic module estimates the techno-economic lifecycle costs arising from the integrated TERA framework and optimisation process. A detailed analysis of each module is not given in this paper due to the scope of this study. However, we anticipate that they will be described in the accompanying paper that is being prepared for publication.

Figure 5 shows the TERA optimisation flowchart based on the optimisation problem formulation.

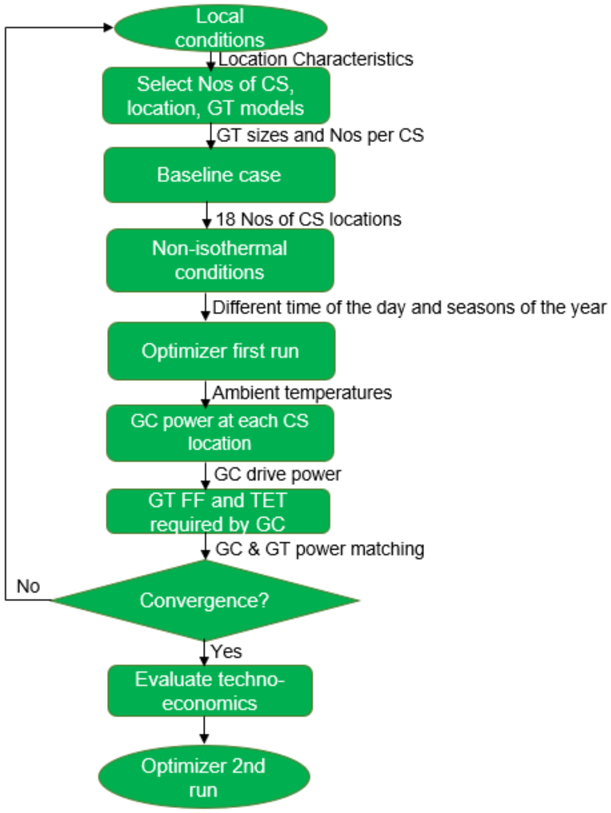

FIGURE 5: TERA OPTIMISATION FLOWCHART

The optimisation problem is formulated following the steps described below. We selected the required number and sizes of gas turbine models dependent on the local conditions at each station. Consequently, we defined the baseline case which is made up of eighteen numbers of compressor stations at fixed locations along the pipeline route. Thereafter, we determined the ambient condition at each compressor station at non-isothermal conditions for the optimised cases. This was done for varying times of the day and at different seasons of the year based on the optimiser's first run. The ambient conditions consider the variation in elevation along the pipeline route as shown in the pipeline elevation-distance profile in Figure 6. The result is the ambient temperatures at the optimised station location. Subsequently, the optimisation strategy evaluates the gas compressor power requirement at these ambient temperatures at different seasons of the year at non-isothermal conditions. We evaluated the gas turbine fuel consumption and the turbine entry temperature needed by the gas compressor. We noted the outcome of the matching between the gas turbine and the gas compressor if the optimisation scheme attains convergence. The iteration procedure is repeated if the fractional difference between the gas compressor power requirement and the gas turbine power is less than 0.1 until convergence is achieved. Thereafter, the optimisation scheme estimates the project's techno-economics appropriately. This optimisation procedure is repeated by changing the locations of the compressor stations along the pipeline route until optimal compressor station locations are achieved. These optimised station locations give the optimal lifecycle cost for the project considering the scenarios utilised in this study.

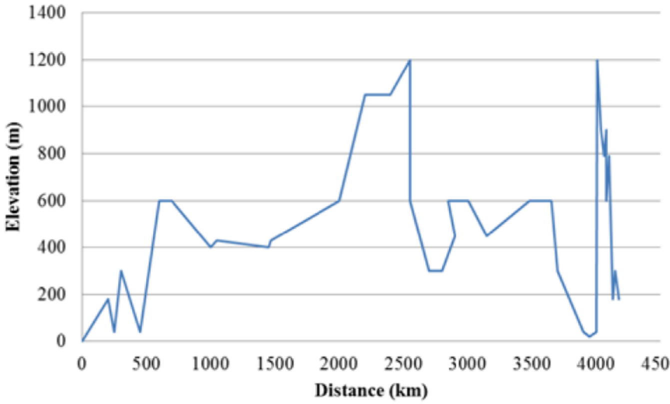

FIGURE 6: PIPELINE ELEVATION-DISTANCE PROFILE [23]

2.1.4 Decision Variable, Objective Function and Constraints

The compressor station location L was selected as the decision variable. L was initialised with a value of 200 km at the beginning of the optimisation process. The range of L for the first compressor station location is from a minimum of 200 km to a maximum of 400 km. The selected gas turbine sizes are assumed constants for each scenario throughout the optimisation process. This is because a constant pipeline thickness was employed in this study. Therefore, the compressor station sizes were not considered in order not to exceed the natural gas pipeline strength requirements. However, future work will include the compressor station size as an additional decision variable under different pipeline thicknesses. Moreover, the selected turbo-compressor models vary for each scenario. This establishes that the power variation is also taken into account in the optimisation process.

The objective function of the techno-economic optimisation process is the lifecycle cost of the compressor station and pipeline systems. The lifecycle cost includes the gas turbine costs, gas compressor costs, pipeline costs, auxiliaries cost, fuel cost, and maintenance cost. We aim to minimise the lifecycle cost for each scenario considered in this study. Our objective is to find the best scenario that gives the lowest lifecycle cost and highest net present value.

The constraint is the pipeline's maximum allowable operating pressure (MAOP) which depends on the gas compressor's power based on the chosen gas turbine models. This constraint was imposed to guarantee that the gas compressor provides the necessary pressure at the pipe suction for continuous natural gas transportation in the pipeline.

The techno-economic optimisation problem to optimise the compressor station and pipeline systems is formulated as follows:

Minimise the objective function:

$$L_c(L) = GT_c(L) + GC_c(L) + P_t(L) + P_{aux}(L) + F_{lc}(L) + M_{lc}(L) \tag{11}$$

Subject to the constraint:

$$P_1 \leq 10^4 \tag{12}$$

$$P_G \leq 0.9P_T \tag{13}$$

$$2 \times 10^2 \leq L_1 \leq 4 \times 10^2 \tag{14}$$

$$L_{n,min} \leq L_n \leq L_{n,max} \tag{15}$$

Where:
L_c = Techno-economic lifecycle cost, $
GT_c = Gas turbine cost, $
GC_c = Gas compressor cost, $
P_t = Pipeline cost, $
P_{aux} = Auxiliaries cost, $
F_{lc} = Fuel consumption cost, $
M_{lc} = Maintenance cost, $
$L_1, \ldots L_n$= Optimised compressor station locations, km

3. RESULTS AND DISCUSSION

The optimised lifecycle cost for the considered scenarios is shown in Figure 7. The lifecycle cost increases during the optimisation process until convergence is achieved. There is an improvement in the lifecycle costs between the optimised scenarios and the baseline case. The optimised lifecycle cost was reduced by 11.11%, 10.07%, 9.22%, and 12.95% in scenarios 1, 2, 3, and 4, respectively compared to the baseline case. The main reason for the reduction in the lifecycle cost is due to the fewer number of compressor station locations along the pipeline route in the optimised scenarios compared to the baseline case. Consequently, this leads to lower fuel and maintenance costs.

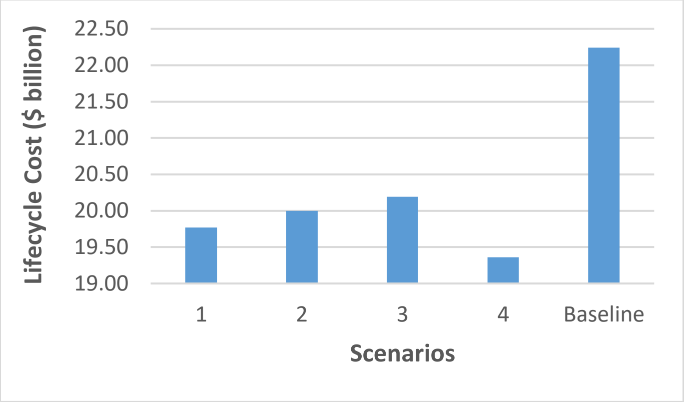

FIGURE 7: OPTIMISED LIFECYCLE COSTS

The optimisation results for scenario 1 show sixteen numbers of compressor station locations along the pipeline route. The lifecycle cost reduces from $22.24 billion in the baseline to $19.77 billion in scenario 1. The optimised compressor station locations are at 1, 28, 55, 82, 109, 135, 162, 188, 213, 240, 266, 292, 318, 344, 369, and 395 segments of the pipeline.

The optimisation results for scenario 2 show thirteen numbers of compressor station locations along the pipeline route. The lifecycle cost reduces from $22.24 billion in the baseline to $20.00 billion in scenario 2. The optimised compressor station locations are at 1, 35, 68, 101, 134, 167, 200, 233, 266, 298, 331, 363, and 395 segments of the pipeline.

The optimisation results for scenario 3 show twelve numbers of compressor station locations along the pipeline route. The lifecycle cost reduces from $22.24 billion in the baseline to $20.19 billion in scenario 3. The optimised compressor station locations are at 1, 36, 71, 106, 141, 175, 209, 244, 277, 312, 346, and 379 segments of the pipeline.

The optimisation results for scenario 4 show twelve numbers of compressor station locations along the pipeline route. The lifecycle cost reduces from $22.24 billion in the baseline to $19.36 billion in scenario 4. The optimised compressor station locations are at 1, 38, 76, 113, 150, 186, 222, 260, 296, 332, 368, and 408 segments of the pipeline. Table 1 shows the optimized compressor station location at various segments of the pipeline.

TABLE 1: COMPARISON OF THE OPTIMISED CS LOCATIONS

	Pipeline segments			
Station No	**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
1	1	1	1	1
2	28	35	36	38
3	55	68	71	76
4	82	101	106	113

5	109	134	141	150
6	135	167	175	186
7	162	200	209	222
8	188	233	244	260
9	213	266	277	296
10	240	298	312	332
11	266	331	346	368
12	292	363	379	408
13	318	395		
14	344			
15	369			
16	395			

Our findings show that the compressor station locations vary with the gas turbine models utilised in this study. This is illustrated by the different types of gas turbines used for the considered scenarios and the baseline case. They yield varying optimised compressor station locations in terms of the pipeline segments. The reason is because the gas turbine power depends on the gas compressor power requirement which is impacted by the compressor station location characteristics. These location characteristics includes the ambient condition, elevation, and distance.

We compared the results of the SIMULINK optimisation process with the genetic algorithm optimisation techniques available in the MATLAB toolboxes. Figure 8 depicts the results obtained for scenario 2 employing the genetic algorithm method.

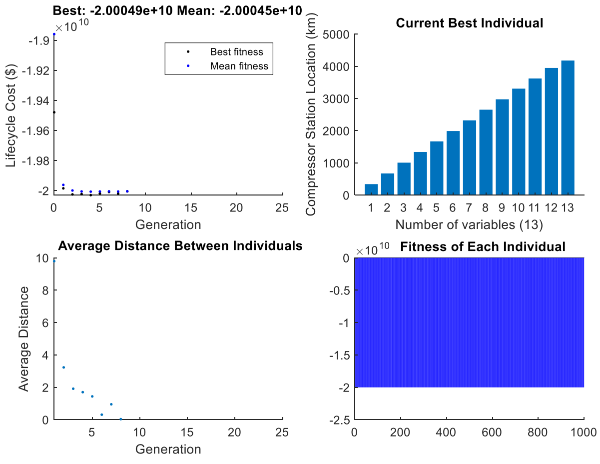

FIGURE 8: OPTIMISED LIFECYCLE COST FOR SCENARIO 2 USING GENETIC ALGORITHM

The top left shows the lifecycle cost in terms of best fitness and mean fitness values against the number of generations. This is for 25 generations and a population size of 1000 as shown in the bottom right for the fitness of each individual. The bottom left shows the average distance between individuals during the optimization process. The top right shows the current best individual in terms of the optimized compressor station locations along the pipeline route. The lifecycle cost in terms of the mean fitness value increases during the optimization process until convergence is achieved. This is because high fuel consumption is needed to generate the required power to compress the natural gas to its maximum distance.

Table 2 shows the outcome of the results obtained for the comparison process for scenario 2.

TABLE 2: COMPARISON OF THE OPTIMISED CS LOCATIONS AND LIFECYCLE COST FOR SCENARIO 2

	Location (km)		
Station No	**Simulink**	**GA**	**Baseline**
1	0	0	0
2	341.3	341.4	240
3	674.0	673.7	480
4	1007.9	1007.9	720
5	1339.0	1339.1	960
6	1669.4	1669.3	1200
7	1990.4	1990.0	1440
8	2322.4	2322.0	1670
9	2653.1	2652.7	1920
10	2976.0	2975.8	2150
11	3306.4	3306.5	2380
12	3622.9	3622.5	2610
13	3948.6	3948.7	2840
14			3070
15			3300
16			3530
17			3760

	Location (km)		
Station No	**Simulink**	**GA**	**Baseline**
18			3990
Lifecycle cost ($ billion)	**20.003**	**20.005**	**22.24**

The comparison of results shows good agreement between the SIMULINK optimisation process and the genetic algorithm. They yield the same number of compressor station locations for scenario 2. Considering the SIMULINK approach, the optimal compressor station locations are observed to converge to the desired local minimum solution of the lifecycle cost. This is based on a defined tolerance limit of 1e-9. Therefore, the optimal compressor station locations are close to the global optimal solution since the lifecycle cost is a differentiable convex function of the compressor station location. In a convex function, the line segment between any two points on the function's curve lies above or on its curve. More so, knowing that for a convex function, the local minimum solution is also the global minimum [34]. However, the optimised solutions for the genetic algorithm optimisation techniques are normally close to the global optimal solution of the lifecycle cost. In both cases, the comparison results show that the optimal compressor station locations are near the global optimum. The results obtained for the SIMULINK optimization process for scenario 2 as shown in Table 2 shows an improvement in the lifecycle cost estimation compared to the genetic algorithm. This improvement is sufficient to justify the efforts involved in the SIMULINK optimization method.

The results obtained illustrate the advantages of the SIMULINK optimisation method utilised in this study. This is the first time this optimisation method has been applied to a compressor station location optimisation. Thus, demonstrating the novelty of the developed optimisation model in this present study.

3.1 PIPELINES PRESSURE PROFILES

Figure 9 shows the segmented pipeline pressure profiles at various compressor station locations for the baseline case and scenario 1. The Trans-Saharan gas pipeline is made up of 419 pipeline segments.

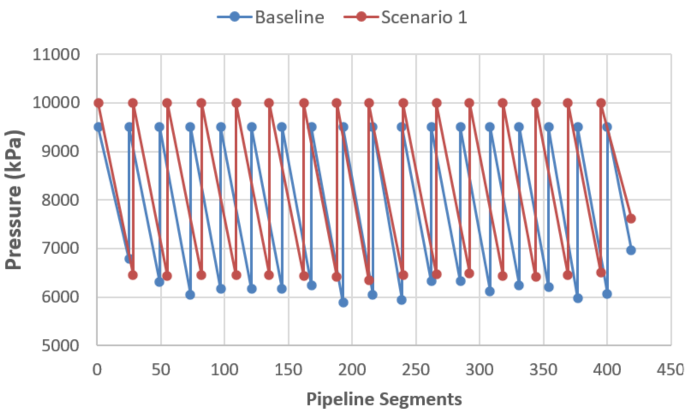

FIGURE 9: PIPELINE PRESSURE PROFILE FOR THE BASELINE AND OPTIMISED CASE

The compression ratio is the ratio of the compressor discharge pressure to its suction pressure. The compressor discharge pressure is the MAOP of the pipeline in this study. The MAOP of the pipeline is 9500 kPa for the baseline case and 10000 kPa for the optimised case. Considering the baseline case, this discharge pressure at the MAOP drops to 6785 kPa at the 25th pipeline segment. Similarly, by considering the optimised case of scenario 1, this discharge pressure at the MAOP drops to 6456.7 kPa at the 28th pipeline segment of the 419 segments Trans-Saharan gas pipeline. Consequently, a second compressor station is required at these pipeline segment locations. This is because the first compressor station has reached its maximum compression ratio needed to compress the natural gas flowing through the pipeline to the maximum distance. This optimisation procedure continues until the necessary number of compressor stations that are required to compress the specified quantity of natural gas through the segmented pipeline is reached. Similar configurations of turbo-compressor units were employed for this optimisation study. This choice of similar unit configuration will lead to spare part management and reduce the number of maintenance cycles required. However, the exception occurs at the last compressor station location for each optimised scenario. This location needs a smaller turbo-compressor unit to compress the natural gas through the segmented pipeline to the final delivery point of 4180 km.

3.2 SENSITIVITY ANALYSIS ON NET PRESENT VALUE

The results of the net present value analysis for the optimised cases at a 15% discount rate are presented in this section. Scenario 1 has a net present value of $16.07 billion, scenario 2 has a net present value of $21.58 billion. At the same discount rate, the net present values are $24.97 billion and $28.77 billion for scenario 3 and scenario 4 respectively.

Figure 10 shows the effect of the discount rate on the net present value.

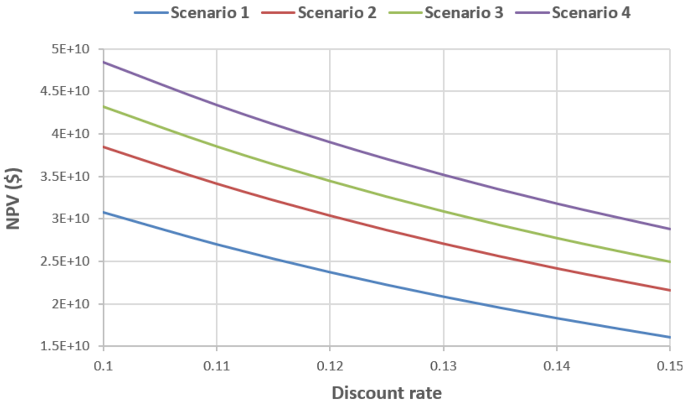

FIGURE 10: VARIATION OF NET PRESENT VALUE WITH DISCOUNT RATE

The results indicate that an increase in the net present value is observed with a decreasing discount rate for all scenarios. The result further showed that the highest net present value at all discount rates occurs in scenario 4. Furthermore, scenario 4 has been shown to have the lowest lifecycle cost. This is due to the fewer number of turbo-compressors installed per compressor station. The 117 MW capacity gas turbine unit consists of an intercooler system which makes it an efficient engine. Therefore, leading to lower fuel consumption and a reduction in the maintenance routine required. Consequently, the overall results show a choice for scenario 4 which has the lowest lifecycle cost, highest net present value and thus the lowest risk among the considered scenarios.

The results have shown the significance of the optimisation process employed in this study with compressor station location optimisation as the decision variable.

4. CONCLUSION

This study has presented a techno-economic optimisation of the compressor station and pipeline segments using compressor station location as the decision variable. This is based on the TERA framework which can determine the optimal compressor station's locations while optimising for the lowest lifecycle cost of the whole project. It was established that:

- 16, 13, 12, and 12 compressor stations are needed along the pipeline routes for the optimised cases of scenarios 1, 2, 3, and 4 respectively. This is in comparison to 18 compressor stations for the baseline case.
- the optimised lifecycle cost reduces by 11.11% in scenario 1, 10.07% in scenario 2, 9.22% in scenario 3, and 12.95% in scenario 4 compared to the baseline case.

The analyses using the SIMULINK optimisation method are consistent with the result of the genetic algorithm optimisation procedure. They show the same number of compressor station locations for each scenario. More so, their lifecycle cost estimations are comparable to each other. Consequently, illustrates the significance of the SIMULINK optimisation methods. This is the first time this optimisation method has been applied to compressor station location optimisation.

This study would serve as a useful decision-making tool for any government involved in policy analysis focusing on the natural gas pipeline industries. Furthermore, it can assist the Nigerian government to design and develop the proposed Trans-Saharan Gas Pipeline project. Moreover, it can guide pipeline investors involved in long-distance gas pipelines to make the best decision in the selection of the most cost-effective compressor-turbine configuration.

A detailed evaluation of each module described in the methodology section is not given in this paper due to the scope of this study. However, we anticipate that they will be described in the follow-up study in future work. Furthermore, the selected gas turbine installed power output was assumed constant for each scenario throughout the optimisation process as described in section 2.1. The constant value for the gas turbine installed power output is due to the utilization of a constant pipeline thickness in this study. Therefore, this study did not consider the compressor station sizes in order not to exceed the natural gas pipeline strength requirements. However, we anticipate including the compressor station size as an additional decision variable under different pipeline thicknesses in future work. Moreover, the selected gas turbine models are different for each scenario. This establishes that the power variation is also considered in the optimisation process.

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Techno-economic optimisation of gas compressor station location as a decision variable

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