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Genetic Algorithm Optimization of Crude Oil Pipeline Operations for Wax Control: A Case Study of CNPC-Niger Petroleum Company

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ABSTRACT

Wax formation and deposition in crude oil pipelines pose a very significant challenge, such as flow restriction, increased cost of maintenance and potential shutdowns. The goals of this study are to reduce wax accumulation in the China National Petroleum Corporation-Niger Petroleum (CNPC-NP) pipeline network, which connects the Agadem oil fields to the SORAZ refinery, by optimizing critical operating conditions. The Reliability of Aspen HYSYS for analyzing wax behavior was validated by the simulation model that closely matched the real-world data, with a simulated flow rate of 182.49 m³/h with, only 0.27% higher than the actual 182 m³/h. The study suggested changing the operating condition using a genetic algorithm method of optimization, which indicates a slight increase in the pressure from 0.6 MPa to 0.65 MPa, while decreasing in temperature from 51°C to 48.5°C and a potential increase in the flow rate to 187.49 187.49 m³/h. Furthermore, the results of the optimization led to a decrease in wax thickness from 0.058 mm to 0.0409 mm, which indicated an improvement in pipeline operating conditions. Also, the economic analysis revealed, the total capital investment was roughly $3.3 million, and the annual operating expenses were estimated to be $2.4 million. The financial indicators include an Internal Rate of Return (IRR) of 9%, a Net Present Value (NPV) of $2.14 million and a Profitability Index (PI) of 1.99, all of which were higher than the IRR of the current CNPC-Niger Petroleum, which was 8%. The results show that the economic performance of the crude oil pipeline system can be improved, and wax formation risk can be effectively decreased by combining simulation-driven decision-making with strategic operational parameter adjustment.

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1. Introduction

In the global energy supply chain, pipeline transportation of crude oil is one of the most essential means. Wax formation and deposition, however, are a recurring operational problem in this field that can result in decreased flow efficiency, higher energy usage and when crude oil is transported under less-than-ideal thermodynamic circumstances, especially when the temperature drops below the wax appearance temperature (WAT), wax precipitation usually happens in such situations, resulting in total pipeline blockage [1]. When crude oil is transported under less-than-ideal thermodynamic circumstances, especially when the temperature drops below the wax appearance temperature (WAT), wax precipitation usually happens in long-distance pipeline that travels through areas with varying environmental and operational conditions, like the CNPC-Niger Petroleum (CNPC-NP) pipeline network from Agadem oil field to SORAZ refinery, which is particularly affected by this phenomenon.

Many studies have looked into ways to reduce wax formation, from pigging operations to chemical treatments and thermal insulation [2]. Optimization of the operational parameters like temperature, pressure and flow rate is still a viable and economical strategy, though. More thorough analysis and predictive modelling of such systems are now possible thanks to recent developments in computational tools and algorithms. Among these, genetic algorithms (GAs) have demonstrated a great deal of promise in resolving intricate, nonlinear pipeline operations optimization issues [3]. Genetic algorithms can iteratively converge toward ideal solutions for minimizing wax formation while preserving operational and financial efficiency by simulating natural selection processes [4].

Genetic algorithms (GAs) have been used in wax-related prediction and control, often by tuning learning models or hybrid intelligent systems. For instance, a GA-optimized least-squares SVM enhanced wax precipitation forecasting from compositional inputs, demonstrating GA's ability to navigate nonconvex parameter spaces common in flow-assurance datasets. Likewise, fuzzy–GA approaches have been reported for modeling wax deposition under multivariate operating conditions, emphasizing the value of evolutionary search when mechanistic models are uncertain or data are noisy[5]. Beyond direct wax prediction, GAs (sometimes combined with particle swarm optimization) have been employed to optimize pipeline thermal and insulation configurations, balancing heat loss, cost, and operability to reduce wax formation. At the network and operations level, GA variants have been used for optimal pipeline design and steady-state operation under nonlinear, discrete, and continuous constraints (such as compressor counts and flow rates), as well as for temperature calibration and estimation tasks within transient models. Collectively, these studies demonstrate that GAs are well-suited for the multi-objective, constrained, and highly nonlinear nature of wax control and pipeline optimization problems, motivating our GA formulation and performance metrics [6].

Genetic algorithm (GAs) has been widely used in optimization of various of numerous of oil and gas pipeline systems, including leak detection, energy efficiency and flow assurance optimization [6]. Moreover, many studies have also explored the use of GAs for wax deposition and prediction in cold climates and offshore environments, where low ambient temperature exacerbates the risk of paraffin build-up [7]. These works demonstrate the flexibility of GA-based approaches in handling nonlinear optimization challenges typical of wax control scenarios. However, despite these advancements, lack of research applying GA techniques to onshore crude oil pipeline networks in Sub-Saharan Africa, particularly within the Sahel region. These region presents unique environmental and operational constraints such as high diurnal temperature fluctuations, limited insulation infrastructure and logistical difficulties in chemical pigging that differ markedly from offshore systems. This study addresses this gap by implementing a GA-based optimization method implemented in MATLAB software incorporated with an ASPEN Plus simulation tool, specifically tailored to Sahelian pipeline conditions, with the objectives of minimizing wax deposition through strategic adjustment of the operational parameters such as flow rate, temperature and pressure. This target approach not only enhances flow assurance but also contributes a novel regional perspective to the broader body of GA-based pipeline optimization. Also to evaluate performance improvements, a comparison between optimized and existing parameters was carried out. Furthermore, an economic investigation was conducted to determine whether putting the optimized operational strategy into practice would be financially feasible.

The main findings of this study discovered that the genetic algorithm-based method of optimization can greatly improve the pipeline performance, but if certain parameter interactions are not appropriately taken into consideration, they may inadvertently increase wax thickness. However, the economic metrics (NPV, IRR, and PI) of the optimized model were all favored, suggesting that simulation-driven decision-making has the potential to enhance flow assurance and economic return in the crude oil transportation system. This study adds to the expanding corpus of research on pipeline engineering computational optimization and offers useful advice to operators dealing with wax-related issues in comparable environmental settings.

2. Materials and Methods

2.1. Materials/Tools

Table **1** presents the lists of materials, equipment and their uses proposed to carry out this research work.

Table 1: List of materials, equipment, and their uses proposed for this research work.

S. NO	Equipment/Tools	Model Specification	Uses
1.	Data from CNPC-NP		Uses for the study
2.	Laptop Computer	1 TRB, 8 GB RAM	Use for software installation
3.	Aspen HYSYS	Version 14.0	Modelling pipeline network
4.	Fluid package	Peng-Robison	Thermodynamic Solver
5.	Aspen Economic Evaluation	Version 14.0	Conduct an economic analysis
6.	MATLAB	Version 2023b	Use for Optimization
7.	@Risk	Version	

2.2. Methods

The critical operational data was first collected in the step of genetic algorithm optimization of the operational parameters of the CNPC-Niger petroleum pipeline network from Agadem to the SORAZ refinery to control wax formation and deposition. These parameters included temperature, pressure, flow rate and crude oil composition, which are essential for predicting deposition tendencies and modelling of wax behaviors [8]. These variables are the fundamental building blocks for creating a reliable simulation model using Aspen HYSYS version 14.0. Thus, Aspen HYSYS is a well-known process simulation tool for crude oil transportation and flow assurance studies, which was used to model and validate the pipeline system [9]. After the Aspen Plus model validation, a Genetic Algorithm (GA) optimization was implemented in MATLAB (version 2022b) environment, which was used to optimize the simulation model. The Gas has been successfully used in the optimization of energy systems and they are well known for its ability to handle complex and non-linear engineering challenges [10]. The primary goal of this research work is the application of GA to reduce wax deposition while enhancing flow assurance and increasing operational reliability across the crude pipeline network.

However, the economic evaluation was carried out according to industrial standard procedures to assess the capital expenditure, operating expenses and some other important economic metrics such as Net Present Value (NPV), Internal Rate of Return (IRR) and Profitability Index (PI) [11]. Table **2** presents the parameters used to perform the investment analysis and evaluate the project execution plan, while Table **3** presents the investment parameters. The methodological steps include simulation, genetic algorithm optimization and economic evaluation, using the procedure outlined in the Flow chart as shown in Fig. (**1-4**), respectively.

Furthermore, a Monte Carlo simulation was set up to assess the variability and uncertainty in the pipeline operation outcomes under different wax deposition scenarios. A Monte Carlo simulation approach was employed. A total of 10,000 simulation runs were conducted to ensure statistical stability and convergence of the results. of the output variables in line with established recommendations [12]. Input parameters were characterized using [specify distributions, e.g., normal, or lognormal distributions, selected based on empirical data and previous studies, with parameters (mean, standard deviation, skewness) estimated using economic indicator tools. The simulation results are reported with 95% confidence intervals, computed using the percentile method, providing a rigorous measure of the uncertainty in predicted outcomes [13]. These details enhance the transparency and reproducibility of the computational approach.

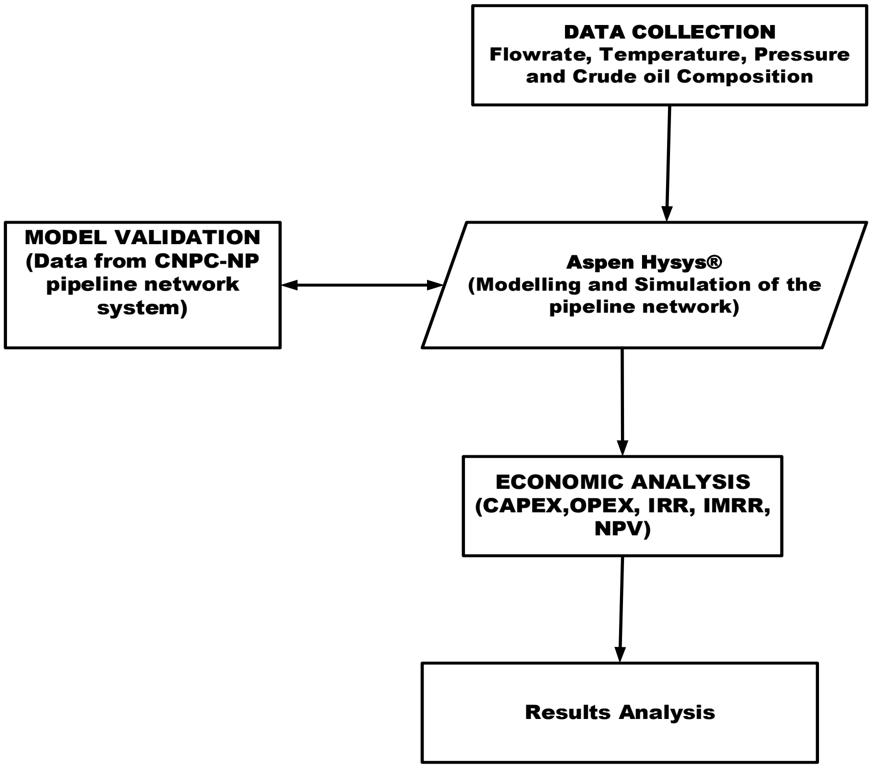

Figure 1: Methodological block process optimization and economic analysis petroleum pipeline network of CNPC-NP.

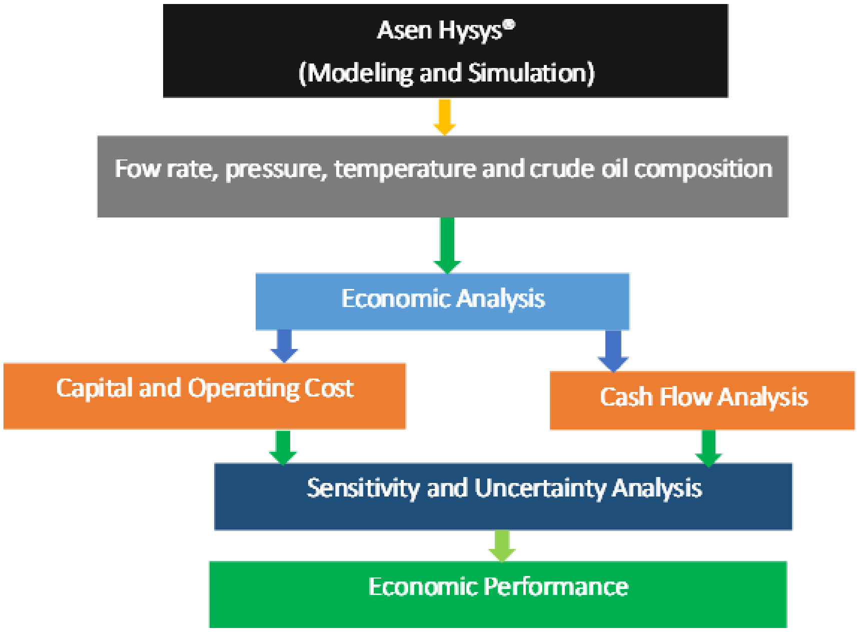

Figure 2: Flowchart-based process optimization and economic evaluation of the CNPC-Niger petroleum pipeline network.

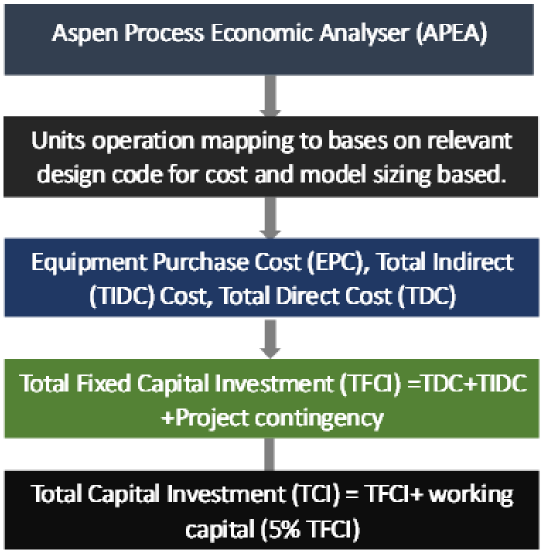

Figure 3: Aspen economic analyzer method of cost estimation.

Table 2: Cost of purchased equipment/materials for each unit.

Equipment/Material	Capacity	Cost (USD)	Reference
Crude Oil	1barrel	64.84	[14]
Steam	1Kg	0.15	[15]
Water	1Kg	0.025	
Diesel	1Kg	1.56	
Spliter		245,680	
Valves		25,259	
Dryer		156,532	
Heater		544,800	
Mixer		150,000	
Pump		120,000	[16]
Pipeline segment	12m	6,200	

Table 3: Investment analysis input parameters.

Name	Units	Items
Period Description		Year
Number of weeks per hour	Weeks/Period	52.0
Number of Periods of Analysis Tax	Percent/Period	25.0
Interest Rate/Desired Rate of Return	Percent/Period	2.0
Economic life of the Project	Percent/Period	25
Salvage Value (Percent of Initial Capital Cost)	Percent/Period	
Depreciation Method		Straight line
Escalation parameters		

Table 3 (Contd….)

Name	Units	Items
Project Capital Escalation	Percent/Period	1.5
Products Escalation	Percent/Period	2.5
Raw Material Escalation	Percent/Period	1.5
Operational and Maintenance Labour Escalation	Percent/Period	1.5
Utilities Escalation	Percent/Period	1.5
Project Capital Parameters		
Working Capital Percentage	Percent/Period	5.0
Operating Cost Parameters		
Operating Charges	Percent/Period	1.0
Plant Overhead	Percent/Period	1.0
General And Administrative Expenses	Percent/Period	1.0
Facilities Operation Parameters		
Facility Type		Pipeline
Operation Mode		Continues Process
Operating Hours Per Period	Hours/Period	8400
Process Fluid		Liquids

Source: Timilsina, *et al*. [17].

2.2.1. Aspen HYSYS Model Development

The CNCP-Niger Petroleum crude oil pipeline network from Agadem to SORAZ refinery was modelled and simulated using Aspen HYSYS software. Peng-Robison computational thermodynamic model was used as the potential fluid package due to its flexibility, wide data bank and ability to provide good calculations in the oil and gas-related field. According to De, *et al*. [18] specified that the Aspen Plus simulator is a very comprehensive tool in process and design engineering, which can replicate between 98 and 99% of chemical process operations. In the context of this study, the CNCP-Niger Petroleum crude oil pipeline network from Agadem to SORAZ refinery was simulated using inlet parameters listed in Table **4** and the corresponding unit operations Aspen HYSYS block models are described in detail in Table **5**. Furthermore, the crude oil assay components included in the simulation model are presented in Table **6**. The following assumptions were listed to simulate as follows:

1. Simulation was conducted at a steady state condition.
2. Negligible heat transfer.
3. Pipe segments represent the pipeline system.

Table 4: Inlet Parameters for ASPEN HYSYS Simulation.

Properties	Unit
Inlet Pressure	0.7 MPa
Inlet Temperature	70 ^oC
Flowrate	182 m^3/h

Table 5: Description of unit operations used for ASPEN HYSYS Process Design CNCP-NP Agadem to SORAZ refinery crude pipeline network.

Unit Operation Block Specification	Aspen HYSYS Block Specification	Description
Heater	HEATER	Heating of crude streams
Pump	PUMP	Pumping of crude oil
Valve	VALVE	Liquid holding
Pipeline	PIPE SEGMENT	Used for the pipe flow network
Split	SPLIT	Splitting crude streams
Mixer	MIXER	Mixing two or more streams

Table 6: lists CNPC- NP-crude assay components used for the modeling and simulation.

Component Name	Type	CAS-Number
H2O	Pure Component	
Propane	Pure Component	
i-Butane	Pure Component	
n-Butane	Pure Component	
i-Pentane	Pure Component	
n-Pentane	Pure Component	
NBP[0]110*	Oil Hypothetical	Blend-1
NBP[0]138*	Oil Hypothetical	Blend-1
NBP[0]163*	Oil Hypothetical	Blend-1
NBP[0]188*	Oil Hypothetical	Blend-1
NBP[0]213*	Oil Hypothetical	Blend-1
NBP[0]238*	Oil Hypothetical	Blend-1
NBP[0]263*	Oil Hypothetical	Blend-1
NBP[0]288*	Oil Hypothetical	Blend-1
NBP[0]313*	Oil Hypothetical	Blend-1
NBP[0]338*	Oil Hypothetical	Blend-1
NBP[0]362*	Oil Hypothetical	Blend-1
NBP[0]388*	Oil Hypothetical	Blend-1
NBP[0]412*	Oil Hypothetical	Blend-1
NBP[0]437*	Oil Hypothetical	Blend-1
NBP[0]462*	Oil Hypothetical	Blend-1
NBP[0]487*	Oil Hypothetical	Blend-1
NBP[0]512*	Oil Hypothetical	Blend-1
NBP[0]537*	Oil Hypothetical	Blend-1
NBP[0]562*	Oil Hypothetical	Blend-1
NBP[0]587*	Oil Hypothetical	Blend-1
NBP[0]613*	Oil Hypothetical	Blend-1

Table 6 (Contd….)

Component Name	Type	CAS-Number
NBP[0]638*	Oil Hypothetical	Blend-1
NBP[0]662*	Oil Hypothetical	Blend-1
NBP[0]687*	Oil Hypothetical	Blend-1
NBP[0]712*	Oil Hypothetical	Blend-1
NBP[0]737*	Oil Hypothetical	Blend-1
NBP[0]762*	Oil Hypothetical	Blend-1
NBP[0]787*	Oil Hypothetical	Blend-1
NBP[0]825*	Oil Hypothetical	Blend-1
NBP[0]875*	Oil Hypothetical	Blend-1
NBP[0]925*	Oil Hypothetical	Blend-1
NBP[0]975*	Oil Hypothetical	Blend-1
NBP[0]1025*	Oil Hypothetical	Blend-1
NBP[0]1075*	Oil Hypothetical	Blend-1
NBP[0]1125*	Oil Hypothetical	Blend-1
NBP[0]1175*	Oil Hypothetical	Blend-1
NBP[0]1251*	Oil Hypothetical	Blend-1
NBP[0]1372*	Oil Hypothetical	Blend-1

2.2.2. Genetic Algorithm Optimization

The operating parameters were optimized using a Genetic Algorithm (GA) to minimize the wax deposition and improve the crude pipeline efficiency. The equation coded was developed to run in the MATLAB version 2023b environment [19].

2.2.2.1. Assumptions for the Optimization

Below are some of the assumptions made to carry out the Genetic Algorithm optimization of the CNCP-NP pipeline network crude to mitigate wax formation via improving the operating conditions of the crude pipeline.

I. Objective

Minimize wax formation risk function (a simplified proxy based on subcooling below the wax appearance temperature (WAT), low flow velocity, and low pressure).

II. Target variable

T = temperature (°C)

P = Pressure (MPa)

Q = Flowrate (m^3/h)

III. Constraint ranges

Temperature (40-80°C)

Pressure (0.5-8 MPa)

Flowrate (100-200 m^3/h)

IV. Wax appearance temperature

The benchmark Wax Appearance temperature (WAT) for Niger Crude oil is 40°C.

V. Pipeline specification

The pipeline is modeled with 1 initial station, 5 intermediate stations and 1 terminal station.

VI. The Genetic Algorithm (GA)

GA control parameters used in this study were as follows; population size: 50, cross probability: 0.8, mutation probability: 0.05, number of generations: 200, stopping criteria: the algorithm terminated either upon reaching the maximum number of generations.

2.2.2.2. Development of the Wax Thickness Model for the CNPC-Niger Crude Oil Pipeline System

Wax deposition is a critical flow assurance challenge in crude oil pipeline transportation, particularly for waxy crudes like those produced in Niger and transported via the CNPC-NP pipeline network system. As crude oil cools below its wax appearance temperature (WAT), paraffin waxes begin to precipitate and adhere to the inner pipe wall, progressively restricting flow and increasing energy demand for pumping.

To mitigate operational risks and optimize maintenance interventions such as pigging and thermal management, it is essential to develop a reliable predictive model for wax thickness under varying operational and environmental conditions.

I. Model formulation

Based on empirical analysis and observed deposition behavior, the wax thickness (in millimeters) in the pipeline is modelled as a multivariable nonlinear function of key influencing parameters. Equation 1 represents the mathematical model developed connecting the response, wax deposition, and independent variables (temperature, pressure, and flow rate).

$$Wax\ deposposition\ thickness(mm) = aP^2 + bT + CQ^{-0.5} + dPT - eT^2 \tag{1}$$

Where:

- P: Pressure in the pipeline (MPa);
- T: Temperature of the crude oil (°C);
- Q: Flow rate of crude oil (m^3/h);
- a, b, C, d, e: Empirical coefficients determined via optimization based on simulation data.

II. Justification of model terms

Each term in Equation (1) is included based on physical understanding and prior studies of wax deposition in crude oil pipelines:

- $a.P^2$: The capture pressure is a nonlinear impact on wax solubility. Wax tends to stay dissolved at higher pressure, but complicated behaviors that are better modeled quadratically arise over long distances of pressure change.
- $b.T$: Wax deposition is directly and linearly impacted by temperature. Wax begins to precipitate as the temperature falls below WAT. Therefore, thicker deposition is correlated with lower temperature.
- $C.Q^{-0.5}$: The influence of shear on wax buildup is respected by the inverse square root of the flow rate. Increase the flow rate to cause more shear at the pipeline wall, which dislodges the developing layer and lowers the deposition rate. The selected exponent t illustrates how cleaning efficiency decreases as flow increases.
- dPT: Combined effects of temperature and pressure on wax solubility and deposition kinetics are reflected in this interaction term; wax stays more soluble at high temperature and pressure, which decreases deposition.

III. Regression method

The regression was performed using a least square fitting approach in MATLAB, using a dataset comprising of 89 operational points from different flowlines across Agadem field. Multicollinearity was checked using the Variance Inflation Factor (VIF) and all variables were found to be independent (VIF<5). Residuals were normally distributed with no evident pattern, indicating a good fit.

i. Empirical coefficient

The coefficients obtained from the regression analysis are presented in Table **7**.

Table 7: Result of coefficient obtained from regression analysis.

Coefficient	Value	p-Value
A	-0.0024	<0.001
B	0.015	0.003
C	-0.12	<0.001
D	0.45	<0.001
E	2.1	<0.001

All the coefficients in above Table **7** is statistically significant at a 95% confidence level ($p<0.05$).

ii. Mathematical model validation

The model was validated against 30 additional data points not used in regression, yielding an R^2 of 0.91 and a mean absolute error (MAE) of 0.17 mm. These metrics indicated strong predictive performance within the study operating range.

2.2.3. Integration of Economic Analysis with Technical Optimization

In addition to the Genetic Algorithm optimization aimed at minimizing wax deposition, an economic analysis was conducted to assess the financial feasibility of the optimized operating conditions, while reducing wax deposition is critical for improving flow assurance and system reliability, it equally important to ensure that the optimized parameters are economically viable for industrial implementation.

The economic analysis evaluates key cost components including energy consumption, operating and maintenance cost due to wax removal and potential production downtime. The inclusion of the economic analysis ensures the proposed solution is not only technically sound but also sustainable and financial stand point.

3. Results and Discussions

3.1. Model Validation

Fig. (**4**) illustrates how Aspen HYSYS simulation results were validated by comparing them with the actual field data from the CNCP-Niger Petroleum crude oil pipeline system, which transports crude from Agadem to the SORAZ refinery. The key significant indicators to determine the capability of the model to simulate the real-world operating circumstances are temperature, pressure, and flow rate; they are also assessed in this comparison. The actual operating temperature of the crude oil at the delivery site is 42 °C, despite the Aspen HYSYS simulation predicting a somewhat higher temperature of 51°C. The 2.5 °C discrepancy is most likely due to modelling assumptions about heat losses, insulation performance and ambient heat coefficients. Heat dissipation in a real-world pipeline system is instigated by several factors, including inadequate insulation, the ambient temperature effect, and the pipeline burial depth conditions, all of which may have been idealized in simulation [20]. Although this temperature difference is notable, it is still within acceptable operating limits for crude oil transportation, where the temperature impacts viscosity but doesn't often pose a significant safety risk. This match suggests that the pressure drop modeling within HYSYS, considering pipeline length, elevation, and frictional losses, is well-calibrated. In pipeline simulation, pressure prediction accuracy is critical for equipment sizing, pump selection, and integrity management. There is a reasonable agreement between the simulation and the field reassessment, which both displayed an exit pressure of 0.5 MPa [21].

The measured volumetric flow rate is 182 m3/h, while the simulated value is 182.4875, which differs by a small amount of 0.27%. This high degree of agreement demonstrated that the model correctly mimics the fluid phase behaviors, pipeline routing and stream future and has a strong mass balance closure. These minor deviations could stem from rounding between the Real-world data system and simulation results [22]. Nonetheless, the results validated that the simulation is a reliable tool for operational and engineering design throughout prediction and performance optimization. The results presented by the model and simulation demonstrate a strong correlation with field conditions across all key parameters. This validation supports the use of ASPEN HYSYS for further sensitivity analysis, debottlenecking studies, and operational optimization in the CNPC Niger pipeline network.

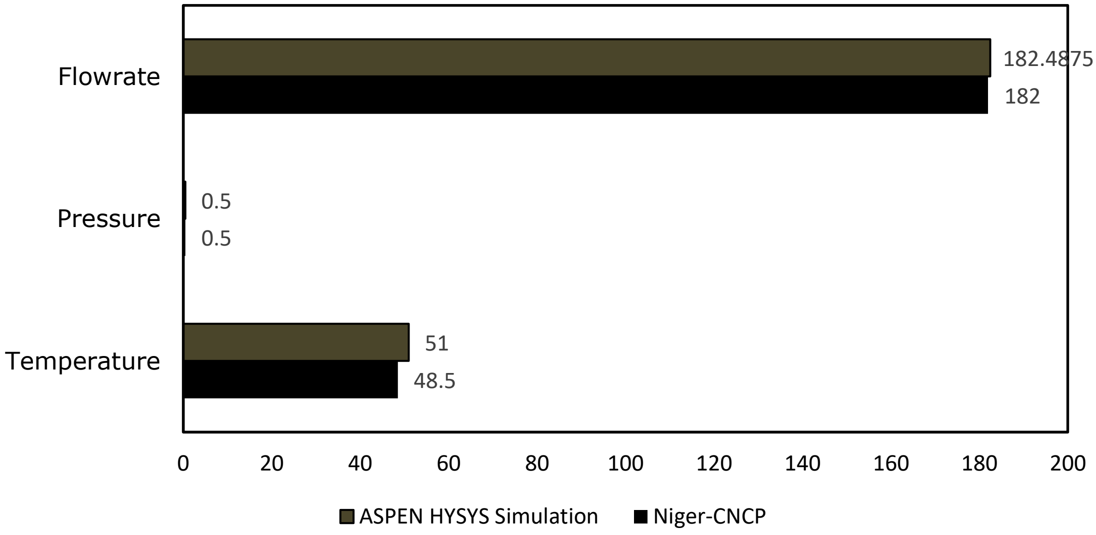

Figure 4: Aspen HYSYS model validation.

3.1.1. Mass Balance

The thermal behaviors, pressure distribution and volumetric flow rate characteristics across the pipeline segments and processing stations are provided by the material balance analysis carried out using Aspen HYSYS for the CNCP-NP crude oil pipeline system, which runs from the Agdem Central Processing Facility (CPF) to the SORAZ refinery. A summary of the critical flow parameters seen at various nodes across the pipeline network is shown in Table **8**.

Table 8: Material balance around each station.

Name	Crude from CPF	HEAD	ET40H
Temperature [°C]		60.00	60.03
Pressure [MPa]	70.00	0.90	0.85
Liquid Volume Flow [m^3/h]	182.00	105.00	105.00
Name	ET-30H3	ET-30H3-1	ET-3OH3-2
Temperature [°C]	42.00	42.04	42.07

Table 8 (Contd….)

Name	Crude from CPF	HEAD	ET40H
Pressure [MPa]	0.77	0.67	0.72
Liquid Volume Flow [m^3/h]	50.40	50.40	50.40
Name	ET-O4O-OUT-223	ET-404-OUT13	ET-404-OUT14
Temperature [^oC]	36.429	36.42	33.49
Pressure [MPa]	0.64	0.64	0.63
Liquid Volume Flow [m^3/h]	157.50	157.50	157.50
Name	BA-ET-401	BA-ET-402	BA-ET-403
Temperature [^oC]	30.51	30.51	30.62
Pressure [MPa]	2.33	2.34	2.55
Liquid Volume Flow [m^3/h]	120.48	120.48	120.48
Name	SR-ET-30H14	SR-ET-30H15	VENT
Temperature [^oC]	30.40	30.41	30.42
Pressure [MPa]	2.60	6.08	6.08
Liquid Volume Flow [m^3/h]	126.77	126.77	80.00
Name	HT1OUT	HTOUT2	HTOUT3
Temperature [^oC]	78.00	78.02	78.81
Pressure [MPa]	7.000	6.00	7.00
Liquid Volume Flow [m^3/h]	74.24	74.24	74.24
Name	OUTLET5	OUTLET6	TO HEATING STATION NPO 5
Temperature [^oC]	55.12	58.12	60.00
Pressure [MPa]	2.60	2.60	2.50
Liquid Volume Flow [m^3/h]	181.24	181.24	182.24
Name	TM-OUT5	TM-OUT6	TO THE REFINERY
Temperature [^oC]	50.00	51.01	51.00
Pressure [MPa]	0.58	0.57	0.50
Liquid Volume Flow [m^3/h]	120.48	120.48	182.48

The crude oil starts from the CPF at a 182m^3/h flow rate, with a corresponding temperature and pressure of 70°C and 0.7 MPa, respectively. As the flow reaches HESD and ET4oH, the temperature declines to 60°C, possibly due to heat loss during transmission, but pressure marginally increases to 0.9MPa at HESD, suggesting a local compression change [23]. This portion shows a regulated distribution of early processing, with flow rates stabilizing at 105m3/h. stations ET-30H3, ET-30H3-1, and ET-30H3-2, experience a further decline in temperature to approximately 42°C. The constant volumetric flow rate (50.4M^3/h) between these stations suggested little leaks, while the small pressure changes from 0.77MPa to 0.71 MPa represent the small losses from friction changes. according to the design criteria, these results show how a steady flow situation with a regulated pressure drop [24].

Nodes ET-040-OUT-223, OUT13, and OUT14 continue to have temperatures between 33.5 and 36.4 °C and the pressure drops slightly from 0.64MPa to 0.638MPa. This small pressure drop across multiple outlets illustrates the effectiveness of pipeline design and thermal insulation, which reduces the Joule-Thomson cooling effect and promotes constant flow conditions. In contrast. The BA-ET series unit operates at slightly higher pressure between

2.43 and 2.56 MPa and relatively lower temperature around 30.55°C. these findings indicated that higher pressure likely implies the presence of a pump station designed to maintain flow momentum and prepare the crude for the subsequent heating process [25].

The constant volumetric flow of 120.49 m³/h throughout these units indicated effective stream consolidation buffer storage management. Potential gas compression procedures are suggested by the SR-ET units and VENT, which recorded a peak pressure of 6.08MPa. The temperature stays steady at about 30.4°C, despite elevated pressure. This is a popular tactic for preserving system pressure balance and guaranteeing operational safety and efficiency. Controlled vapor release, which could be caused by the observed flow rate of 80 m3/h at the vent site [26].

In line with thermal reconditioning before the final delivery, the heat segment (HT1OUT to HTOUT3) exhibits high temperature (Up to 78°C) and pressure between 6.0 and 7.0MPa. the following outlets (OUTLET5, OUTLET6, TM-OUT5/6) prove negligible loss across terminal lines by maintaining flow homogeneity at 181 to 183m^3/h despite exhibiting moderate thermal losses. With the final flow delivery to the refinery as 182.49 M^3/h at 51°C and 0.5MPa temperature and pressure, the modeled system exhibits effective material balance closure. these finding shows operational efficiency with minimal variation in mass flow rate and pressure drop. However, this confirms the accuracy of the Aspen HSYSY model in representing the actual circumstances of the CNCP-Niger Petroleum Pipeline network from Agadem to the SORAZ refinery.

3.2. Genetic Algorithm Optimization

To minimize wax deposition under various operating conditions, the wax formation in the CNPC-Niger Petroleum crude oil pipeline system was optimized using a genetic algorithm (GA), as shown in Table **9**. The table below presents the results, which compare the operational parameters used with those established during GA Optimization.

Table 9: Lists CNPC-Niger petroleum crude assay components used for the modeling and simulation.

Parameters	Actual CNCP-Niger	Genetic Algorithm Optimization
Temperature (^{O}C)	51	48.5
Pressure (MPa)	0.6	0.65
Flowrate (M^3/h)	182	187.49
Wax formation Thickness(mm)	0.0058	0.00409

As presented in Table **9**, the Genetic Algorithm (GA) optimization suggested lowering the pipeline operating temperature from 51°C to 48.5°C. Huang, *et al*. [27] noted that a minor temperature drop can still be effective if they are offset by factors like higher shear rate, which maintains acceptable wax levels. Even though this modification brings the operating conditions closer to wax appearance temperature (WAT), it may increase the likelihood of wax precipitation. Furthermore, the optimization model also recommended a pressure increase from 0.6 to 0.65 MPa; this change is consistent with the study of Xu, *et al*. [28], who discovered that increased pressure improves overland flow assurance in crude oil pipelines by increasing wax solubility and delaying the start of deposition.

Additionally, the flow rate was increased slightly from 183 m³/h to 187.49 m³/h. Higher flow velocities produce wall shear stress, which is essential for preventing wax deposition since it continuously breaks up and removes the nascent wax layer according to Ridzuan and Al-Mahfadi [29]. Together with an increase in the flow pressure, this increase in flow rate maintains dynamic flow conditions that deter wax formation. Together, these modifications suggest a well-coordinated control approach, whereby a slight drop in operating temperature does not always increase the likelihood of wax deposition due to the compensatory effect of higher pressure and flow rate.

Interestingly, under the optimal conditions, the thickness of the wax layer decreases from 0.0058mm to 0.0409 mm, respectively. Even though it may appear counterintuitive, considering the measures taken to reduce deposition, Xie, *et al*. [30] emphasize that non-linear and independent combinations of temperature, pressure and flow rate can occasionally produce unexpected consequences. Despite improvement in solubility and shear stress, local conditions might have promoted greater deposition in some pipeline segments. This highlights the importance of employing multi-objective optimization methods and more comprehensive spatial models to capture these complexities in future studies.

Overall, the GA optimization provided important insights into how operational parameters influence wax deposition in the CNCP-Niger crude oil pipeline. The temperature, pressure and flow rate changes offer promising chances to improve flow assurance and deal with wax-related problems, even though further study may be required to completely comprehend the observed increase in wax thickness.

3.3. Economic Analysis

Based on vendor quotes, the stream process price (Table **2**) was established and matched the total cost estimates obtained from mass balance values shown in Table **8**. The economic analysis was conducted using a crude oil sales price of $6.484 per barrel according to the daily crude market forecast, which represents a $1.66 per barrel cost reduction compared to the initial rate of $7.65 per barrel used in the current CNCP-Niger Petroleum pipeline network from Agadem to SORAZ refinery. Energy analysis was used to determine the utility requirements, and the first quarter 2025 pricing benchmark was used to estimate the associated expenses. Using mass and energy balances and equipment design parameters derived from the simulation model. The Aspen Economic Analyzer (APEA) version 14.0 was used to assess the overall capital operating expenses. It was predicted that the optimized operating conditions of the Agadem to SORAZ pipeline network would require a total capital investment of about $3.3 million. This estimate covers every significant aspect of capital cost distribution, including contingencies, contract fees, the installation of a diesel generator, engineering and procurement, steel structure and civil engineering works, piping and instrumentation and acquisition and installation of equipment.

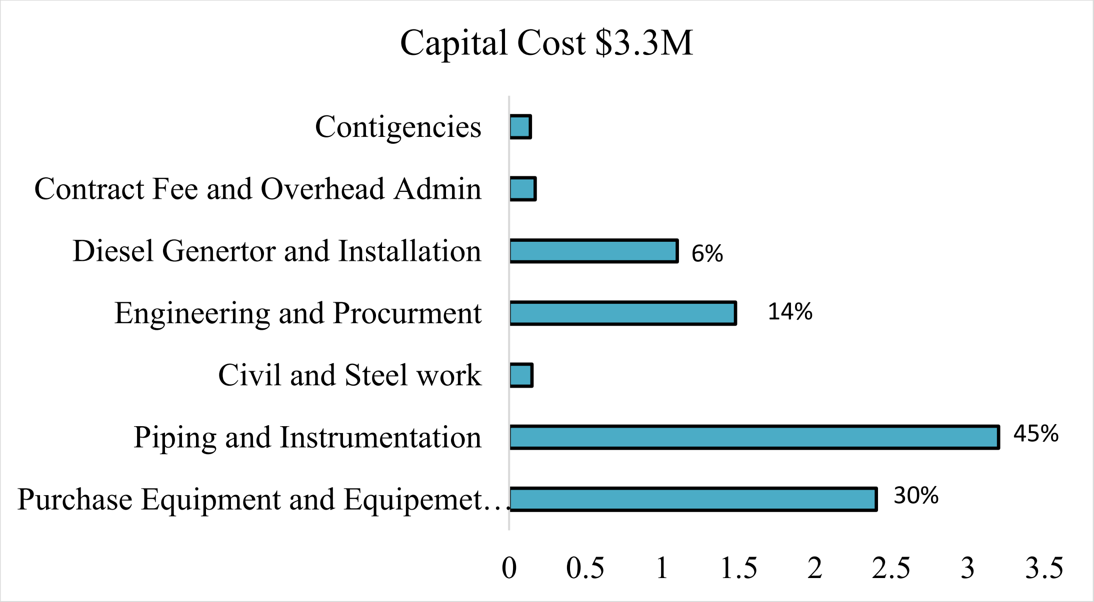

Figure 5: Capital cost distribution.

The capital cost distribution (Fig. **5**) shows that, at roughly 45% of the overall capital cost, plumbing and instrumentation are the most expensive components. Design, engineering and procurement expenses come in at 14%, followed by the acquisition and installation of equipment at 30%. The installation of the diesel generator accounts for about 6% of the total cost. The updated configuration and price structure show a more inexpensive and practical project arrangement when compared to the existing CNCP-Niger Petroleum crude oil pipeline from the established to the current state.

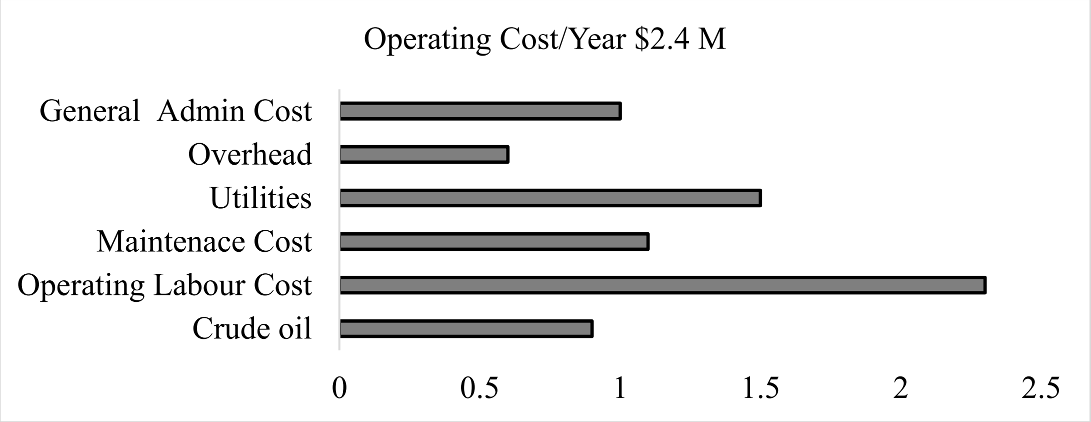

Figure 6: Operating cost distribution.

As shown in Fig. (**6**), the optimized operating condition modelled for Agadem to SORAZ crude oil pipeline network operating cost distribution consists of essential elements, such as general administration expenditures, overhead costs, utilities, maintenance, operating labor and crude oil costs. The highest percentage of them, roughly 48% of the overall operating expenses, is attributed to labor costs. Maintenance comes in at 14% and utilities at 19%. Thus, at hourly rates of $1.50 and $2.50 per worker, respectively, the total running cost, which is expected to be $2.4Million annually, is greatly influenced by these manpower requirements.

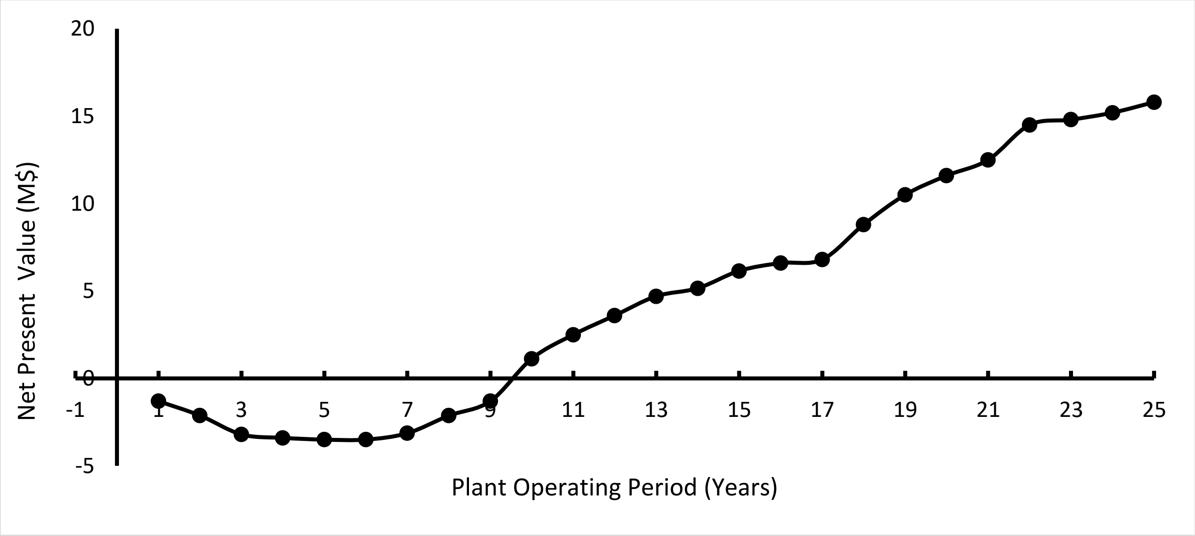

Figure 7: Net present values against operational years.

The Agadem to SORAZ crude oil pipeline network, the Net Present Value (NPV) trajectory over a 25-year lifespan is shown in Fig. (**7**). During the first 12 years, the NPV stayed negative, suggesting an economically unprofitable time. Following the time frame, the break-even point, where NPV equals zero, corresponds, indicating the beginning of economic viability. This began around 10 years ago, and the initiative started to turn a profit. this stage is often called the payback period or the discount payback period (DPP). The payback period for the existing pipeline operating is 10.35 years. A financial indicator called the profitability Index (PI) compares the present value of future cash inflows to the initial investment to determine how profitable an investment is overall. A project may be lucrative if its discounted benefit outweighs its expenses, as indicated by the profitability index (PI) greater than 1. A PI of 1.99% for the optimized Agadem to SORAZ pipeline indicated a solid economic proposition because it indicates that for every dollar invested, present-value returns are anticipated. The discount rate at which the net present value (NPV) of the overall project cash flow equals zero is known as the internal rate of return (IRR). It acts as a standard by which to measure how desirable investments are. This, with an IRR of 9%, the optimized Agadem to SORAZ crude oil pipeline has a better expected investment than the existing CNCP-Niger Petroleum crude pipeline network, which has an IRR of 8%. This implies that with comparable risk profiles, the pipeline project is more financially appealing.

3.3.1. Economic Sensitivity Analysis

The influence of major cost components on both capital and operating expenditure was evaluated using a Monte-Carlo sensitivity analysis that considered ±20% variation in cost for installed equipment, instrumentation, operational labor, utilities, maintenance costs and raw material.

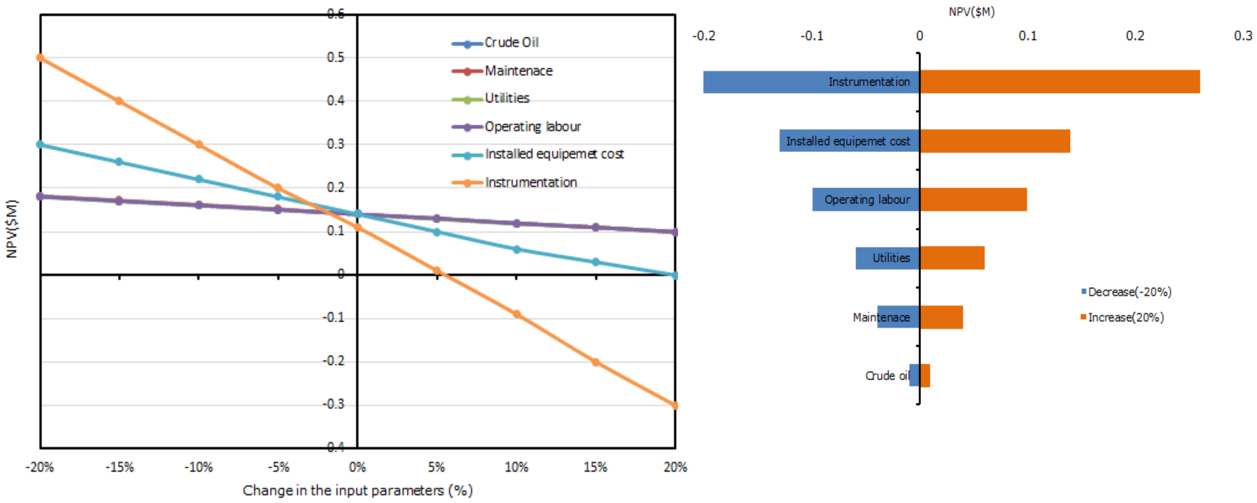

Figure 8: (**a**) Monte Carlo simulation and (**b**)Tornado sensitivity analysis.

The system economic feasibility is unaffected by an increases instrumentation cost by 10%; the break-even point is reached at 15%, after which profitability starts to fall (Fig. **8a**) the sensitivity analysis shows that in the Tornado Chart (Fig. **8b**), instrumentation expenses have the biggest impact on the Net Present Values (NPV), flowed by installed equipment prices. Economic performance is greatly improved by a 20% decrease in the instrumentation cost, which raises the NPV from $2.14Million in the base the CNCP-Niger Petroleum crude pipeline to almost $3.3Million.

In a similar strain, a 15% increase in installed equipment costs keeps the system economically viable, whereas a 20% increase reaches breakeven. Additionally, a 20% decrease in these expenses results in a slight increase in NPV, raising it to $2.27 million. However, the NPV is only little affected by changes in operational labor, utilities, feedstock and maintenance expenses, falling within a range of ±20%. This suggests that these factors have relatively small effects on the project's profitability [31, 32].

The results of the findings imply that the project economic prospects nay enhanced by switching from a fully automated instrumentation and control system as envisaged in the base case of the CNCP-Niger Petroleum crude pipeline case to semi semi-automated configuration. Such a shift would result in a significant drop in overall capital expenditure by lowering the expenses of installed equipment as well as instrumentation [33].

4. Conclusions

The existing CNCP-Niger Petroleum crude oil pipeline network was mimicked successfully by the Aspen HYSYS simulation model to examine the wax formation and deposition using existing data. The results of the simulation show a small difference of 0.27%, the simulated flow rate of 182.49 m^3/h and the actual crude pipeline flow rate of

182 m^3/h, which nearly matched, demonstrating a reasonable mass balance and accurate pipeline representation under identical operating temperature and pressure conditions.

The Genetic Algorithm optimization predicts the optimum operating condition as 48.5C °C, 0.65 MPa and a flow rate of 187.49 m3/h, with the corresponding wax thickness of 0.0409mm compared to the existing crude pipeline with wax of 0.0058mm at 51C °C, 0.6 MPa and a flow rate of 182 m3/h,

The economic evaluation of the optimized CNCP-Niger Petroleum crude pipeline simulation predicts a total capital investment of approximately $3.3 million, with the highest costs attributed to pipes and instrumentation (45%), equipment procurement and installation (30%) and design, engineering, and procurement (14%). An estimate of $2.4 million would be spent annually on operations, of which 48% would go into labour, 19% would go toward utilities and 14% for maintenance. With an Internal Rate of Return (IRR) of 9%, a Net Present Value (NPV) of $2.14 million and a Profitability Index (PI) of 1.99%. Key financial measures demonstrate greater economic feasibility than the current crude pipeline network.

Conflicts of Interest

The authors declare no conflicts of interest.

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Data Availability

The data is available from the corresponding author upon reasonable request.

Author Contributions

Maman Ibrahim Salissou.: Conceptualization, Methodology, Software. Maman Ibrahim Salissou.: Data curation, Writing- Original draft preparation. Usman Hassan.: Visualization, Investigation. Ibrahim Ayuba and Usman Hassan.: Supervision. Usman Hassan and Ibrahim Ayuba: Software, Validation. Inuwa Amed Mohammed.: Writing-Reviewing and Editing.

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