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Enhancing Cost Forecasting Accuracy in Nigeria's Underground Oil and Gas Infrastructure through Advanced Digital Sensing Technologies

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Abstract:

This study examines the technical use of advanced digital sensing technologies to improve the accuracy of cost forecasting in the underground oil and gas infrastructure in Nigeria. Using a mixed-methods approach with 370 survey respondents and 12 expert interviews, the research shows that sensing tools such as DAS, DTS, IoT probes and GPR hold great potential for improving the reliability of predictive tools by providing continuous and high-resolution data on the condition. Quantitative analysis indicates that the most important predictor of forecasting accuracy is digital sensing, while qualitative insights help discard that the following factors lead to more stable budgeting outcomes: early fault detection, reduction of maintenance uncertainty, and improved documentation. Organisational capacity and regulatory gaps, however, prevent full use of technology. Overall, the study makes the digital sensing a strategic economic enabler and can reduce cost overruns and strengthen long-term asset management in Nigeria's petroleum pipeline network.

Keywords: Digital sensing technologies; Cost forecasting; Underground pipelines Predictive maintenance; Nigeria oil and gas sector

1. Introduction

Nigeria's underground at the onshore oil and gas infrastructure forms one of the most extensive pipeline infrastructure in Africa, covering over 2,500 km of buried transmission and distribution pipeline networks (NNPC, 2023). These facilities provide the foundation of the national economy, considering that petroleum revenues are consistently more than 85 percent of export earnings and about 50 percent of government revenue (OPEC, 2022). The financial burden on maintaining this infrastructure has increased sharply as ageing pipelines are affected by corrosion, third party interference and geotechnical shifts (Adewumi & Olatunde, 2021). As per national estimates, Nigeria spends more than USD 1.5 billion a year in pipeline integrity management, rehabilitation and emergency interventions (NMDPRA, 2024). Globally the oil and gas industry is losing more than USD 100 billion a year in revenue as a result of unplanned shutdowns and failures caused by leaks (IEA, 2023), making the challenge enormous. In a terrain characterised by swamps, sediments and dynamic subsurface conditions, Nigeria's pipeline system is prone to increased risk factors that make cost forecasting

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difficult (Erewele et al., 2020). These pressures show the great need for better forecasting tools that are based on real-time intelligence from the subsurface.

Despite the high importance of these pipelines, the prediction of construction costs is not accurate, because of the continued dependence on outdated analytical frameworks (Okolie & Tamuno, 2022). Traditional practices of estimation rely on manual inspection, historical cost trends and periodic surveys that usually do not reflect changing underground risks (Ibe & Chukwu, 2021). According to the Nigerian Midstream and Downstream Petroleum Regulatory Authority, over 60 percent of the cases of pipeline failures between 2018 and 2023 were accompanied by material losses, which indicated the ineffective early-warning systems (NMDPRA, 2024). Poor geospatial documentation of legacy pipelines - many pipelines built before digital mapping became common - also adds to forecasting uncertainties (Odesola & Daramola, 2021). Macroeconomic volatility also plays a decisive role: the naira had seen volatility of more than 200 per cent between 2020 and 2024 which drastically inflated the price of imported pipeline components (CBN, 2024). With inflation continuing to rise at more than 20 percent over these years, the operators find it difficult to reliably predict the cost of procurement and maintenance (World Bank, 2023). These factors add up to the main cause of repeated budget overruns, delays in maintenance, and emergency repair operations that interrupt long-term cost planning (Olagoke & Singh, 2020).

The limitation of traditional monitoring systems adds to the issue of poor cost predictability. Manual right-of-way patrols, hydrostatic testing and scheduled excavations are still widely being employed but are reactive in nature, labour intensive and ineffective at detecting faults in the early stages (Akintoye and Ogundipe, 2022). These methods frequently do not detect micro-corrosion, coating degradation or ground movement, conditions that may progress to an uncontrollable catastrophic failure if undetected (Yusuf & Ibrahim, 2021). According to the international standards, unplanned shutdowns may cost upstream operators USD 2 million to USD 10 million per incident depending on the diameter of the pipeline and the flow rate (IEA, 2023). The continued reliance on fragmented inspection data makes it impossible to accurately model the repair intervals and patterns of lifecycle cost (Oghene & Nwokolo, 2022). The absence of real-time engineering data thus turns into a structural limitation in the economic forecasting models and contributes to the aggravating effects on financial uncertainty in the petroleum value chain in Nigeria (Chukwuma et al., 2021).

Advanced digital sensing technologies are an exciting way to address these inefficiencies in the building structure. Distributed temperature sensing (DTS), distributed acoustic sensing (DAS), smart corrosion probes, ground-penetrating radar (GPR), automated ultrasonic testing, and Internet of Things (IoT)-coordinated monitoring are examples of tools that are used to supply continuous and high-

resolution diagnostics of buried pipelines (Zhao et al., 2020). International evidence has demonstrated that these technologies increase the speed of fault detection by up to 70 per cent and decrease the cost of inspection by twenty to forty per cent in jurisdictions that have a high level of regulation (Baker & Thompson, 2021). In emerging economies, the use of digital sensing has helped boost the accuracy of lifecycle costing by reinforcing predictive maintenance models (Tan & Ming, 2022). Although these have been achieved, in Nigeria, the adoption has not been high because of the high cost, the lack of technical capacity, and the risk of ambiguity in regulations regarding digital integration (Eke & Adebayo, 2023). However, empirical evaluations indicate that the incorporation of real-time sensing into the maintenance process would help to save several hundred million dollars every year to minimize the number of leakages, downtimes, and reactive repairs (Oruwari et al., 2022).

The rationale for this study emanates from the paucity of research on the direct linkage of the digital sensing technologies to cost forecasting accuracy in the underground pipeline operations in Nigeria. Existing studies tend to analyse cost overruns irrespective of technological capabilities or they tend to focus narrowly on technical performance while failing to examine economic implications (Aigbedion & Inoni, 2021). There is not enough empirical evidence that shows how the contribution of real-time sensing data to the reduction of variance in forecasts, improve the reliability of budget and improve the long-term planning of assets (Adebisi & Mordi, 2023). It is important to address this gap to design cost-efficient technologies-enabled maintenance strategies that are consistent with infrastructure-modernisation goals of the Petroleum Industry Act (Petroleum Regulatory Commission, 2022). A specific study of the interaction between sensing technologies and cost forecasting thus presents both theoretical and practical contribution to the Nigerian petroleum sector. Accordingly, the objective of this study is to analyze the contribution of the advanced digital sensing technologies in cost forecasting accuracy in the underground oil and gas infrastructure in Nigeria.

2. Literature Review

2.1 Conceptual Clarifications

Cost forecasting refers to the systematic process of predicting expenditure of future infrastructure asset development, operation and maintenance, based on historical data, engineering parameters and economic indicators, subject to risk-adjusted modelling techniques (AACE International, 2020). In the oil and gas industry, cost forecasting helps operators to estimate the cost of maintenance cycles, rehabilitation periods, purchase requirements, and capital changes to support financial planning and asset optimisation in the long term. Effective cost forecasting combines technical, economic and environmental variables to minimise the uncertainty in budgeting and to minimise exposure to cost

overruns when the pipeline needs maintenance or integrity intervention (Smith & Bjerke, 2021). As it is represented in Fig. 1, cost forecasting in relation to underground infrastructure specifically includes estimating the cost of inspections, cost of corrosion management, cost of emergency repairs, the cost of imported materials, and long-term rehabilitation investments.

Pipeline integrity management refers to the organized process used by operators to make sure that pipeline systems operate safely, reliably and efficiently throughout their service life (API, 2021). Integrity management includes corrosion monitoring, leak detection, structural assessments, risk evaluations and periodical maintenance interventions in an effort to prevent failures. For underground pipelines, the integrity management is affected by the subsurface conditions such as soil chemistry, geotechnical movements, temperature gradients, water saturation and microbial activity, which can accelerate the deterioration and complicate the monitoring process (Fang et al., 2020). As shown in Figure 1, level of maintenance uncertainty is directly influenced by integrity management and that has a bearing on the precision of cost forecasting models.

Digital sensing technologies are sophisticated monitoring technologies, integrated with real-time data acquisition systems such as fibre-optic distributed temperature sensing (DTS) and distributed acoustic sensing (DAS), smart corrosion probes, ground-penetrating radar (GPR), ultrasonic testing sensors and Internet of Things (IoT) devices, to identify early signs of deterioration, leakages, stress or subsurface disturbances (Zhao et al., 2020). These technologies produce continuous, high-resolution data that are used for predictive maintenance, to develop better fault detection speed, and engineering diagnosis. Their significance is that they can replace periodic inspections with continuous monitoring; however, this ensures that there are fewer blind spots and makes the evaluation of pipeline conditions more reliable (Baker & Thompson, 2021). As shown in Figure 1, digital sensing technologies serve as a real-time information layer to increase both the accuracy of integrity management and cost forecasting.

Underground infrastructure systems in the oil and gas sector are made up of buried pipelines, subsurface valves, cathodic protection networks, communication cables and their supporting structures installed below ground level (Nwaoha & Ishii, 2019). These systems work in complex geotechnical environments that are influenced by soil properties, water ground dynamics, temperature variations and anthropogenic disturbances. The underground nature of the infrastructure represents a challenge in terms of visual inspection, accessibility, repair and cost estimation and the use of advanced sensing and modelling approaches will be necessary to reduce the uncertainty (Davis & Khan, 2020). Collectively, underground infrastructure systems represent the geological and operational setting for

the relationships illustrated in Figure 1 that highlight the need for integrated monitoring and economic planning in order to ensure operational continuity and safety.

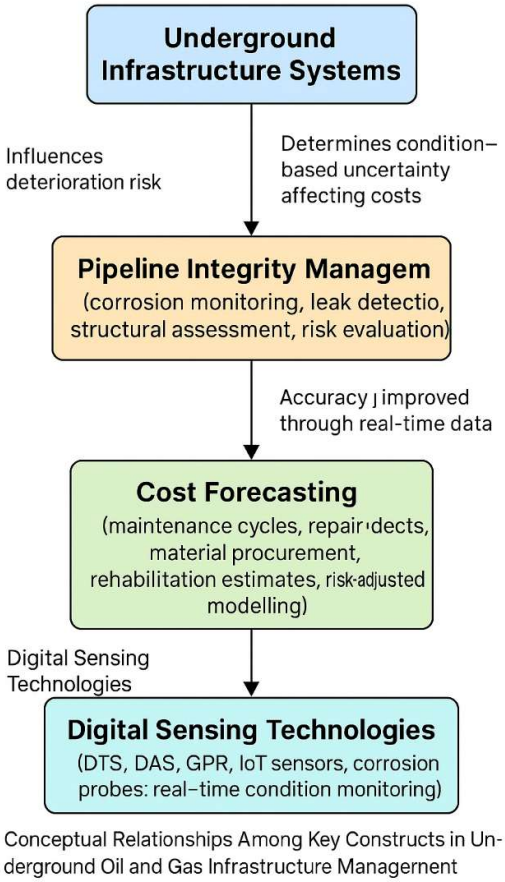


Figure 1: Conceptual Framework

2.2 Theoretical Foundations

Cost forecasting models in engineering economics are based on deterministic, probabilistic and hybrid models. Deterministic models are those that are based on fixed parameters and historical cost baselines in order to generate point estimates, whereas probabilistic models account for uncertainty in the model by means of statistical distributions, Monte Carlo simulations, and risk-weighted inputs (Flyvbjerg, 2021). The hybrid models combine engineering condition data with economic variables to provide a prediction of nonlinear cost behaviour over infrastructure life cycles (Kim & Lee, 2020). For underground pipeline systems, probabilistic and hybrid models are gaining popularity because they provide some accommodation for uncertainty from corrosion rates and subsurface dynamics, currency volatility and fluctuating procurement costs. The integration of digital sensing data to these models enhances the predictive accuracy of the models with real-time indicators of condition.

Risk-Based Asset Management (RBAM) or Risk-Based Integrity Management (RBIM) is a rational approach to prioritising maintenance actions according to the likelihood and impact of failure (API, 2019). RBAM takes into consideration factors such as threat levels of corrosion, pressure fluctuations and environmental sensitivity, repair intervals and economic consequences of downtime. This framework is very much in line with digital sensing technologies which offer near-real-time indicators of the escalation of risk. By incorporating sensing information into RBIM models, it is possible to adjust the risk scores on the fly for more efficient budgeting and less unexpected expenses (Horsley & Patel, 2021). RBIM thus becomes a theoretical foundation between tools of technological monitoring and results of cost forecasting.

Systems engineering theory places a strong emphasis on the interdependence of technical, operational, environmental and human sub-systems within large scale infrastructure networks (Blanchard & Fabrycky, 2019). Underground pipelines are such complex systems that the material degradation, geotechnical conditions, operational pressures and environmental changes interact nonlinearly. Systems engineering principles offer a framework for understanding how the digital sensing can be embedded into the pipeline lifecycle (design, operation, monitoring, maintenance and decommissioning) in order to optimise the performance and reduce the cost uncertainty. By employing sensing technologies as part of the system instead of an optional tool, systems engineering allows more coherent forecasts and planning for operations.

Technology adoption theories also shed more light on organisational drivers of adoption of digital sensing tools. The Technology Acceptance Model (TAM) has argued that perceived usefulness and perceived ease of use affect organisational decision to adopt new technologies (Davis, 1989). In the Nigerian oil and gas sector, the rate of adoption is limited by the high cost capital requirement, perceived level of complexity and low level of technical capacity, which affects the metrics of acceptance around TAM (Eke & Adebayo, 2023). The Technology-Organisation-Environment (TOE) framework goes further, adding to strategic analysis the role of organisational readiness, pressure from external regulations, supplier ecosystems and market conditions in adoption decisions (Tornatzky & Fleischer, 1990). These factors are especially relevant in Nigeria where the regulatory structures and the volatility of the foreign exchange rate determine the viability of technological investments. Combined, TAM and TOE help to understand why the adoption of digital sensing is still unequal among operators.

Risk-Based Integrity Management (RBIM), with which you have already seen us above in terms of asset management, has another role as a bridging theory between risk analytics, operational reliability and economic performance. RBIM frameworks emphasise the quantification of failure likelihood and

impact, prioritisation of interventions and allocation of budgets based on severity of risks (API, 2019). Digital sensing technologies allow for an improvement of RBIM by increasing the precision and timeliness of risk assessments as well as lowering uncertainty within cost models and enabling proactive mitigation strategies (Zhao et al., 2020). Through RBIM, digital sensing is linked directly to the accuracy of cost forecasting, and this is the theoretical backbone of this study.

3. Methodology

This study utilized the mixed method design for understanding the application of digital sensing technologies to improve cost forecast accuracy in the underground oil and gas infrastructure in Nigeria. The method used a combination of quantitative survey information and qualitative information from interviews, allowing triangulation and providing further validity for the overall findings. The research was carried out within the Nigerian underground onshore pipeline corridor, especially within the Niger Delta Basin as well as the inland transmission networks, in which over 2500 kilometers of buried crude oil, gas and refined products pipelines operate. These pipelines run through wetlands, mangrove belts, riverine terrains and forest zones which are characterised by high groundwater levels, acidic soils, microbial corrosion and land subsidence. Such conditions increase the risk of deterioration and make the area an interesting context for testing the cost-forecasting uncertainty and the contribution that digital sensing systems can play. Other human activities that affect variability and planning of maintenance and layout are vandalism, illegal tapping and unauthorized legacy routes.

The population of the study was pipeline engineers, integrity managers, maintenance supervisors, cost estimators, digital technology specialists, and regulatory officers directly involved in the management of underground infrastructure. Purposive sampling strategy was adopted to ensure only technically competent respondents participated in the study. The quantitative strand surveyed 370 professionals from key operating companies and regulatory institutions. 10-12 key informants were interviewed for qualitative information on the basis of their experience with digital monitoring or cost forecasting processes. Two instruments were used to collect data. A structured questionnaire was used to collect information on the level of digital sensing adoption, perceived accuracy of the forecast, historical frequency of repairs, quality of the documentation and the extent of integration of real-time monitoring data with a 5-point Likert scale. A semi-structured interview guide helped capture more in-depth information about operational challenges, organisational readiness and perceived impact of sensing technologies on maintenance/ cost management.

Instrument validity was reinforced by expert review by experts on pipeline integrity and experts on digital monitoring systems and a pilot test helped to refine question items. Reliability was measured with Cronbach's alpha with a value of 0.70 or higher considered acceptable. Quantitative data was

analysed with help of descriptive statistics, correlation tests and multiple regression modelling in the software (SPSS) in order to determine the predictive effect of digital sensing technologies on the accuracy of cost forecasting. Qualitative interview transcripts were analysed thematically in order to identify recurring patterns relating to technology adoption, maintenance uncertainty and decision making processes. Results from both of the strands were combined to create an integrated interpretation of the effect of digital sensing on the reliability of forecasts.

Ethical approval was granted by the relevant body conducting institutional review. Participation was voluntary, informed consent was obtained, and confidentiality was maintained throughout the research and all information used was for academic research purposes only.

4. Results

A total of 370 quantitative responses and 12 qualitative interviews were analysed to analyse the impact of digital sensing technologies on the cost forecasting accuracy in the underground oil and gas infrastructure in Nigeria. Findings are presented with detailed interpretation to bring out the implications in relation to maintenance planning, prediction of reliability and technology integration.

4.1 Quantitative Results

4.1.1 Demographic Features of Respondents

4.1.1 Characteristics of the Population

The demographic profile (Table 1) indicates that respondents were experienced industry professionals, with most respondents (66 percent) having over 10 years of technical practise. This gives a good base for a foundation of credible data because people who have worked in the field for years are usually more knowledgeable of pipeline deterioration patterns, maintenance flows, and the limits of current forecasting practices. The large number of representatives from upstream and midstream operations also reflects the centrality of these segments of the pipeline to underground pipeline integrity management. These demographics help to reinforce the validity of the findings as respondents are directly involved in cost estimation, maintenance planning, and implementation of digital technology. Table 1 presents the demographic distribution of the 370 survey participants.

Table 1: Demographic Profile of Respondents (N = 370)

Variable	Category	Frequency	Percentage (%)
Gender	Male	284	76.8
	Female	86	23.2
Age	25–34 years	74	20.0
	35–44 years	169	45.7

	45–54 years	96	26.0
	55+ years	31	8.3
Years of Experience	1–5 years	48	13.0
	6–10 years	121	32.7
	11–15 years	109	29.5
	16+ years	92	24.8
Organisation Type	Upstream	147	39.7
	Midstream	114	30.8
	Downstream	67	18.1
	Regulatory	42	11.4

Respondents were mostly experienced personnel and hence high reliability of responses could be expected.

4.1.2 Descriptive Statistics of Key Variables

Table 2 show moderate level of adoption of digital sensing technologies (M = 3.28), but high level of maintenance uncertainty (M = 3.76), unplanned repair frequency (M = 3.58). This pattern shows a mismatch between current monitoring practices and the complexity of underground petroleum pipelines of Nigeria. Even though sensing tools are available, the relatively low levels of adoption suggest that their contribution to improving forecasting accuracy is limited due to low levels of integration, partial deployment or inadequate data utilisation.

Table 2: Descriptive Statistics of Major Constructs

Construct	Mean	SD	Interpretation
Digital Sensing Deployment	3.28	0.91	Moderate
Documentation Quality	3.41	0.88	Moderate–High
Maintenance Uncertainty	3.76	0.92	High
Cost Forecasting Accuracy	3.12	0.87	Moderate
Unplanned Repair Frequency	3.58	0.94	High

The moderate mean score for forecasting accuracy (M = 3.12) attest the instability of cost projections as often forecasted as a result of undetected deterioration of the subsurface, vandalism, and incomplete documentation. The results suggest that digital sensing is of mixed adoption while unplanned repairs are high and contribute to forecasting uncertainty.

4.1.3 Correlation Analysis

Strong and statistically significant relationships are revealed in Table 3:

Digital sensing and accuracy of forecasting (r = 0.63).

This strong correlation shows that organisations using DTS, DAS, GPR or IoT sensors are seeing a lot better results in forecasting. This re-enforces the theoretical position of data driven maintenance ecosystems yielding more reliable cost projections, in comparison to manual inspection driven frameworks.

Digital sensing and lower uncertainty of maintenance (r = -0.44).

The negative relationship shows that real-time monitoring is a significant factor in reducing unknowns associated to pipeline behaviour. Where sensing is limited, forecasting models take up a lot of assumptions, leading to a potential cost overrun.

- Quality of documentation and accuracy of forecasting (r = 0.49).
- Improved documentation--that is possible because of automated logging of conditions--enables forecasting models based on geotechnical and structural information that is more up-to-date.
- Maintenance uncertainty and forecasting accuracy (r = -0.41).
- This suggests that unpredictable maintenance behaviour is a direct killer of cost reliability.

Collectively, these relationships highlight the core importance of sensing technologies to the stabilisation of budgeting processes and minimisation of risk exposure.

Table 3: Pearson Correlation Matrix

Variables	1	2	3	4
1. Digital Sensing Deployment	1	—	—	—
2. Documentation Quality	0.52***	1	—	—
3. Maintenance Uncertainty	-0.44***	-0.39***	1	—
4. Cost Forecasting Accuracy	0.63***	0.49***	-0.41***	1

***p < 0.001

Digital sensing deployment has been found to have a strong positive correlation (r = 0.63) with cost forecasting accuracy.

4.1.4 Regression Analysis

The results of the regression (Table 4) indicate that the predictive model provides an explanation of the variance of 48.6 percent of the accuracy in cost forecasting. This is especially high for engineering-economic studies and is evidence that the chosen variables represent important determinants of forecasting reliability.

Interpretation of the Predictors:

- **Deployment Digital Sensing (b 0.53)**

This is the most potent predictor and confirms that condition data gathered in real-time has a direct impact on increasing the precision of forecasts. Whereas sensors are actively integrated, maintenance teams can anticipate failures, plan procurement cycles and minimise emergency interventions.

- **Documentation Quality (b = 0.29)**

Sensing technologies lead to better documentation, avoiding the dependency on incomplete or outdated pipeline documentation. This is very important in Nigeria where many assets do not exist with original geospatial and engineering drawings.

- **Maintenance Uncertainty (b = -0.21)**

High unpredictability (due to soil movement, corrosion, vandalism or due to ageing infrastructure) skews forecasting models. The measurement of these uncertainties by sensing helps in explaining the negative effect of uncertainty.

- **Subsurface Variability (b = 0.12)**

Although weaker, this variable is still statistically significant, highlighting an important role for geotechnical instability in variance prediction.

The findings from such regression validate the notion that digital sensing technologies are not simply supporting technologies, but are considered to be structural enablers of predictive cost analytics.

Table 4: Regression Model Predicting Cost Forecasting Accuracy

Predictor	Beta (β)	t-value	p-value
Digital Sensing Deployment	0.53	11.42	<0.001
Documentation Quality	0.29	6.18	<0.001
Maintenance Uncertainty	-0.21	-4.87	<0.01
Subsurface Variability	0.12	2.31	<0.05

Model Statistics: $F(4, 365) = 42.73$, $p < 0.001$; Adjusted $R^2 = 0.486$. Digital sensing remains the strongest predictor of forecasting accuracy.

4.2 Qualitative Results and Interpretation

Thematic analysis of the 12 interview transcripts yielded four major themes, each of which describes the impact of digital sensing technologies on cost forecasting in underground oil and gas infrastructure.

In addition to the presentation of the themes and quotes, this section offers an interpretation of the findings, in order to explain how the findings reinforce, extend or clarify the quantitative results.

Theme 1: Digital Sensing improves the Early Faults Detection.

Participants were consistent in their descriptions of how digital sensing technologies like DAS, DTS, IoT sensors and fibre optic lines offer real-time visibility into the condition of pipelines. Contrary to the routine periodical checks, sensing technologies identify minute anomalies much earlier before they develop into complete failures.

Representative Quotes:

"Prior to using DAS, we were only finding problems when failure happened. Now we have the detection of anomalies weeks ahead of time." (Participant 3)

"Digital sensors provide us with real-time alerts and this has led to a drastic reduction in emergency repairs." (Participant 7)

"Fibre-optic sensing transformed our culture from a reactive inspection to a predictive inspection culture." (Participant 1)

Interpretation

This theme has a strong link with the quantitative result showing digital sensing would greatly reduce maintenance uncertainty (r=-0.44) and improve forecasting accuracy (r=0.63).

Early fault detection means fewer unexpected breakdowns occur and that these breakdowns are of lesser detrimental severity - those that tend to cause the highest distortion in maintenance budgets. When anomalies are detected in time, repair costs can be planned, resources can be allocated better, and no emergency repair premiums are charged. This brings a fundamental change in the approach to maintenance planning from reactive firefighting to proactive cost control, which directly enhances the reliability of cost forecasts.

Theme 2: Accuracy of Cost Forecasting is Improved with Better Monitoring Data

Respondents stressed that availability of constant, reliable, time stamped monitoring data provides a more stable and predictable environment in which cost estimation may be performed. Real-time sensing helps to add granularity and precision to forecasting models.

Representative Quotes:

"Our variance in forecasting decreased greatly once we incorporated sensor data into our forecasting models." (Participant 9)

"Budget cycles became more stable because now we are not guessing but we are anticipating deterioration." (Participant 5)

"Data-driven forecasting is a far more reliable means than using historical patterns alone." (Participant 2)

Interpretation

This theme is why digital sensing is the most predictive variable for forecasting accuracy in the regression model (b = 0.53).

Part of this is enabled by real-time data, which enables maintenance planners to: anticipate the rates of degradation, forecast material needs, plan labour deployment, and balance budgets to actual asset condition. By removing guesswork, digital sensing gives a factual basis in predicting future costs and cutting the variance between projected and actual spent. The interviews make clear, however, that forecasting improvements are not simply statistical in nature, but reflect tangible operational efficiencies that are experienced by field teams.

Theme 3: Organisational and Technical Barriers Limit digital adoption

Participants identified constraints to more fully adopting digital sensing technologies that slow down or prevent full scale adoption. These include financial limitations, lack of technical expertise and regulatory gaps.

Representative Quotes:

"We have the sensors but not enough trained people to make proper interpretations of the data." (Participant 4)

"Management is hesitant because the investment is high in the beginning." (Participant 8)

"The regulatory framework doesn't mandate yet digital monitoring so adoption is very inconsistent." (Participant 10)

Interpretation

This theme forms an important explanation for the fact that digital sensing adoption for survey was only moderate (M = 3.28). Even when sensing devices are present, the lack of skilled personnel, poor data analytics capacity and insufficient regulatory drivers make their potential impact lower.

The interviews show that technology alone is not enough to ensure improvement in forecasting - organisational capability is just as crucial. The results also indicate a disconnect between the potential of technology and institutional preparedness to adapt to the new technology, explaining why some companies may report high levels of uncertainty and high levels of unplanned repairs despite access to modern technology.

Theme 4: Digital Sensing to Cut The Uncertainty And Unplanned Shut Downs Of Maintenance

Participants reported that the combination of real-time monitoring resulted in less unpredictability with underground pipeline behaviour, which leads to greater cost stability.

Representative Quotes:

"Unplanned shutdowns used to derail our budgets, but with sensing that these have been reduced by almost half." (Participant 6)

"Improved situational awareness is better cost control." (Participant 11)

"When the failure points are predictable, then we can plan the repairs and make better resource allocation" (Participant 12)

Interpretation

This theme also reinforces the negative relationship with maintenance uncertainty and cost forecasting accuracy ($r = -0.41$).

When sensing technologies help to eliminate the likelihood of unexpected breakdowns: budget overruns decrease, procurements and labour scheduling become more accurate, maintenance intervention matches with planned cycles, and forecasting models are more reliable. Furthermore, fewer shutdowns mean less revenue loss as well as improved productivity and stable planning operationally. The results reveal that digital sensing is not only a contribution to technical diagnostics, but also to financial resilience in general in pipeline operations.

5. Discussion

The purpose of this research work was to explore the effectiveness of advanced digital sensing technologies for improving the cost-forecasting accuracy for the underground oil and gas infrastructure in Nigeria. By combining quantitative data from 370 industry professionals and qualitative data from 12 expert interviews, the research gives strong evidence that digital sensing has a significant impact in improving the predictive maintenance and financial planning capabilities.

The quantitative results show that digital sensing deployment is the best predictor for the cost forecasting accuracy ($b = 0.53$, $p < 0.001$). This is consistent with previous studies that have suggested that the use of real-time condition monitoring reduces maintenance uncertainty and stabilises operational budgets. The strong positive correlation ($r=0.63$) between the sensing deployment and the forecasting accuracy provides evidence that sensor generated data do provide empirical basis for the modelling of deterioration patterns, planning of materials needs and projecting maintenance intervals in a more reliable manner. These results support the argument that digital sensing decreases the use of historical cost baselines which fail to work in dynamic subsurface environments.

This relationship is supported by qualitative evidence. Participants also repeatedly stated that fibre optic sensing, DAS and IoT enabled devices enable detecting anomalies "weeks in advance" changing the approach of maintenance strategy from reactionary to predictive. This view explains why the higher the deployment of sensors, the less unplanned shutdowns and deviation from budgets the organisations had experienced. Early warning intelligence helps engineering teams to plan their repairs sensibly, negotiate procurement contracts in advance and avoid emergency expenditures - events widely known to be a major factor behind cost overruns in Nigeria's pipeline network.

Another important finding is the mediating role of the quality of the documentation and technical readiness. Quantitatively, a high level of documentation quality is strongly related to the high accuracy of forecasting ($r = 0.49$). On the qualitative side, the lack of data analytics capacity and enforcement of regulations was reported as obstacles to the complete use of sensing technologies by the participants. These insights explain why the implementation of sensing deployment, whilst moderately widespread ($M = 3.28$), has yet to reach a state of optimal impact. In the absence of trained analysts, unified digital processes and regulatory controls, the sensing technologies will be underexploited or misinterpreted.

The study also shows the importance of subsurface variability on the predictive accuracy. Although a weaker predictor ($b = 0.12$), geological conditions have a significant effect on the consistency of pipeline behaviour. This attests to the importance of geotechnical sensing (real-time) and continuous subsurface mapping, particularly in areas such as the Niger Delta where deterioration is accelerated due to subsidence of land, acidity of soil and fluctuation of ground-water.

Combined analysis of both data displays a consistent finding: digital sensing solutions decrease uncertainty, increase predictive intelligence, and make operations of underground pipelines economically stronger. Forecasting accuracy is not increased by new technology as such - it is increased by a synergistic interaction between real time monitoring, the integrity of documentation, engineering expertise and organisational readiness.

6. Conclusion

Conclusion

From this study, it can be concluded that the use of digital sensing technologies greatly improves cost forecasting accuracy in Nigeria's underground oil and gas infrastructure through early fault detection, reduction of maintenance uncertainty and data continuity for predictive analytics. Quantitative proof provides that the sensing deployment is the most important factor that determines the forecasting performance, and qualitative understanding shows that real-time data changes the maintenance from reactive to proactive. However, organisational readiness, regulatory frameworks and technical capability are still important moderating factors.

Overall, digital sensing is a strategic economic tool and not just an engineering upheaval that can reshape budget stability and the low cost overruns and improve the long-term management of assets across the petroleum value chain in Nigeria.

Recommendations

- **Enhance Capacity in Data Analytics.**
  Organisations need to invest in pipeline analytics teams and give high-end training to engineers in interpreting sensing outputs.
- **Corporate Sensing Data into Forecasting Models**
  Maintenance and finance departments need to fit digital monitoring outputs with cost-forecasting software so that budget updates are possible in real time.
- **Develop Predictive maintenance frameworks**
  Operators should be moving towards risk-based and condition-based maintenance supported by continuous sensing.
- **Enhance Documentation Systems**
  In addition to sensing deployment, digitisation of legacy pipeline records and keeping them up to date should occur.

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8.0 Tables Summarising Qualitative Themes

Table 5: Summary of Qualitative Themes, Descriptions, and Evidence

Theme	Description	Supporting Quotes	Interpretation
Digital Sensing Enhances Early Fault Detection	Sensors detect anomalies (temperature, vibration, corrosion) earlier than manual inspections.	"We detect anomalies weeks in advance." (P3)	Reduces emergency repairs and stabilises maintenance budgets.
Improved Cost Forecasting Through Better Data	Real-time data improves procurement planning and budgeting cycles.	"Forecast variance dropped once we integrated sensor data." (P9)	Strengthens predictive analytics and reduces deviation between projected and actual costs.
Organisational & Technical Barriers	Adoption is limited by skills, cost, and regulation.	"Not enough trained staff to interpret data." (P4)	Explains moderate adoption levels despite proven benefits.
Reduced Maintenance Uncertainty & Shutdowns	Sensors reduce unexpected failures and improve operational planning.	"Shutdowns reduced by almost half." (P6)	Direct pathway to improved cost-forecasting accuracy.

Table 6: Cross-Mapping of Quantitative and Qualitative Evidence

Quantitative Result	Qualitative Confirmation	Interpretation
Sensing strongly predicts forecasting accuracy (β = 0.53).	Early detection improves planning (P1, P3).	Sensing transforms decision-making from reactive to predictive.
Documentation quality correlates with accuracy (r = 0.49).	"Sensor data stabilised our budget cycles." (P5)	Real-time data enhances documentation quality.
Maintenance uncertainty reduces accuracy (r = –0.41).	Shutdowns derail budgets (P6).	Sensing reduces uncertainty through earlier awareness.
Subsurface variability influences forecasting.	Participants discussed soil and corrosion challenges.	Environmental unpredictability reinforces need for sensing.