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A Multicriteria Decision-Making Model Based on the Integration of AHP and Bayesian Decision Trees for Selecting a Method for Replacing Submarine Pipes

Retsa Anugrah Menteng*, Tri Joko Wahyu Adi
Institut Teknologi Sepuluh Nopember, Indonesia
Email: retsa.anugrah@gmail.com*, trijoko@its.ac.id

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ABSTRACT

The X–Y Platform subsea pipeline owned by PT PHE OSES has been operating beyond its design life and has experienced significant degradation, as evidenced by 17 leakage incidents and the installation of nine repair clamps over the past five years. This condition requires strategic asset management decisions that consider not only costs but also technical and safety risks. This study aimed to develop a hybrid decision-making model integrating the Analytic Hierarchy Process (AHP) and the Bayesian Decision Tree (BDT) to determine the optimal pipeline replacement method. In this model, AHP was used to determine the priority weights of five main criteria: Cost, Health, Safety, Security, and Environment (HSSE), Technical, Flow Assurance, and Integrity. Subsequently, the BDT method was applied to combine these weights with historical failure probability data and posterior probability updates to calculate the utility values of four decision alternatives: Full Replacement, Segmented Replacement, Localized Repair, and Do Nothing. The results showed that the Integrity criterion received the highest priority weight (34%). Based on the posterior Expected Utility (EU) evaluation, Full Replacement was identified as the optimal alternative, with the highest EU value of 60.55, outperforming Segmented Replacement (52.23), Localized Repair (43.99), and Do Nothing (30.54). This integrated model provides objective technical recommendations to support management decision-making in effectively mitigating operational risks associated with subsea pipelines under conditions of uncertainty.

INTRODUCTION

The oil and gas industry remains a key pillar of the national energy system and the global economy. Although the global energy transition continues to accelerate, the oil and gas sector still plays a strategic role in supplying transportation fuels, petrochemical feedstocks, and energy for power generation and household consumption. In Indonesia, oil and gas production continues to be optimized through the development of existing fields, the drilling of new wells, and investments in upstream infrastructure (Aprizal et al., 2022; Arifin et al., 2024; Fitnawan et al., 2021; Saptarini & Nainggolan, 2022; Wahjusaputra, 2023). For example, national oil and gas production reached 1.79 million barrels of oil equivalent per day (BOEPD) in 2024 and increased to 1.799 million BOEPD in February 2025, exceeding the 2025 State Budget target of 1.61 million BOEPD.

Despite these achievements, the oil and gas industry faces significant technical challenges, particularly related to subsea infrastructure. Many oil and gas fields have been operating for 30–40 years and are experiencing a natural production decline, requiring technological interventions such as Enhanced Oil Recovery (EOR) and infill drilling. More critically, subsea pipelines connecting offshore platforms to onshore processing facilities continue to deteriorate over time because of corrosion, fatigue, structural damage, and external disturbances such as ocean currents and vessel activities. As illustrated in Figure 1.1, the X–Y pipeline operated by PT PHE OSES experienced more than 17 leakage incidents and required the installation of nine repair clamps over the past five years, highlighting the urgent need for pipeline rehabilitation or replacement (Dixon et al., 2023; Khaing & Yin, 2025; Li et al., 2023; Marshall et al., 2026; Muazu et al., 2025).

Pipeline failures have both economic and environmental consequences, including production losses, repair costs, oil spills, marine pollution, ecosystem degradation, and social and reputational impacts. Therefore, the decision to replace a subsea pipeline should be considered a strategic investment rather than merely a cost burden and should be based on comprehensive analyses of technical, operational, Health, Safety, Security, and Environment (HSSE), financial, and regulatory considerations.

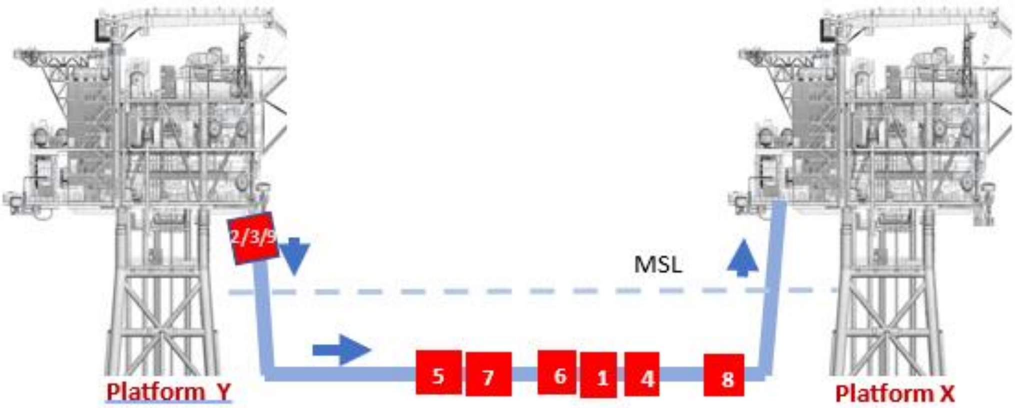

Figure 1. Sketch of clamp installed on Platform X – Y at PT PHE OSES

Currently, the decision-making process for approving pipeline replacement investments at PT PHE OSES is primarily based on technical evaluations and conventional economic analysis, particularly Cost–Benefit Analysis (CBA). However, it has not yet incorporated a structured multi-criteria decision-making framework that systematically weights the factors influencing investment decisions (Bilbao-Terol et al., 2016; Dhochak & Sharma, 2016; Mantogiannis & Katsigiannis, 2020; Sachdeva et al., 2023; Wei, 2025).

In both academic research and industrial practice, various approaches have been proposed to support pipeline maintenance and replacement decisions. Pipeline Integrity Management (PIM) has evolved from conventional visual inspections to risk-based approaches supported by real-time data. Risk-based integrity management has received considerable attention because it incorporates both the probability and consequences of failure into the decision-making process, as highlighted in the review by Q. Xie and Tian (2021). Recent studies have also explored the application of artificial intelligence and simulation techniques, including deep learning, for pipeline failure prediction and inspection optimization. Within the field of Multi-Criteria Decision-Making (MCDM), methods such as the Analytic Hierarchy Process (AHP), Fuzzy AHP, the Weighted Aggregated Sum Product Assessment (WASPAS) method, and their hybrid variants have been widely applied to evaluate alternatives based on technical, financial, and risk-related criteria. For example, Chang et al. (2024) integrated Fuzzy AHP and WASPAS to select internet platforms under conditions of incomplete information, demonstrating how combining MCDM methods can improve decision quality under uncertainty. Similarly, the Fuzzy Analytic Hierarchy Process-based decision tree approach integrated Fuzzy AHP with decision tree analysis to prioritize supply chain attributes, illustrating the potential for combining MCDM techniques with decision tree models.

Although MCDM methods such as Fuzzy AHP and WASPAS have proven effective for ranking alternatives under relatively static conditions, they exhibit important limitations when applied to critical infrastructure characterized by high uncertainty. Conventional MCDM approaches generally treat criterion weights as fixed values, whereas the probability of failure in pipeline integrity management is dynamic and continuously changes as new inspection information becomes available (Kuchekar et al., 2024; Miguel et al., 2025; Toufighi et al., 2024).

Conversely, purely probabilistic models often fail to capture organizational strategic preferences, such as risk tolerance, investment priorities, and qualitative managerial considerations. Therefore, this study adopted an integrated approach combining the Analytic Hierarchy Process (AHP) and the Bayesian Decision Tree (BDT). AHP was selected because of its ability to structure complex multi-criteria problems into a logical decision hierarchy, whereas BDT complemented AHP by incorporating dynamic risk probabilities through Bayesian posterior updating, a capability that is generally unavailable in conventional MCDM methods.

Nevertheless, existing approaches still have several limitations. MCDM methods, including AHP, are susceptible to expert subjectivity in assigning weights and conducting pairwise comparisons. They also have limited ability to represent complex nonlinear interactions among criteria and extreme uncertainty. In contrast, probabilistic and data-driven approaches, such as decision trees and machine learning models, primarily emphasize prediction and classification while providing limited consideration of qualitative factors, multiple decision consequences, and the interpretability required for strategic asset replacement decisions. Furthermore, studies integrating MCDM methods, particularly AHP, with Bayesian Decision Trees in the context of subsea pipeline replacement within the oil and gas industry remain scarce, especially those based on real operational case studies in Indonesia.

To address these research gaps, this study proposed a decision-making framework integrating the Analytic Hierarchy Process (AHP) and the Bayesian Decision Tree (BDT) to evaluate and select subsea pipeline replacement alternatives based on multidimensional criteria, including technical, Health, Safety, Security, and Environment (HSSE), operational, financial, and regulatory considerations. The framework was validated through a case study of the X–Y subsea pipeline operated by PT PHE OSES to compare and verify the performance of the available replacement alternatives. Consequently, this study contributes not only to the academic literature but also provides practical recommendations for oil and gas companies and regulators regarding safe, reliable, and cost-effective subsea pipeline asset management.

This study is expected to provide both academic and practical contributions. Academically, it enriches the literature on multi-criteria decision-making for oil and gas asset management by integrating the Analytic Hierarchy Process (AHP) and the Bayesian Decision Tree (BDT), offers an empirical case study for future research, and demonstrates the complementary application of qualitative and quantitative decision-making techniques. Practically, the proposed framework supports the selection of optimal subsea pipeline replacement strategies that minimize leakage risk, production downtime, and economic losses while enhancing operational safety and environmental protection. Furthermore, the framework can serve as a reference for similar infrastructure asset management projects and indirectly contribute to marine pollution prevention and the long-term sustainability of offshore oil and gas operations.

METHOD

This study employed a quantitative case study approach to develop a multi-criteria decision-making model integrating the Analytic Hierarchy Process (AHP) and the Bayesian Decision Tree (BDT). The research involved a literature review, data collection from secondary internal documents and primary expert interviews using purposive sampling, the identification of four decision alternatives (Full Replacement, Segmented Replacement, Localized Repair, and Do Nothing), and the selection of five evaluation criteria: Cost, Health, Safety, Security, and Environment (HSSE), Technical, Flow Assurance, and Integrity. AHP was applied to derive the criteria weights through pairwise comparisons aggregated using the geometric mean, with consistency verified by a Consistency Ratio (CR) of ≤ 0.10. The resulting weights were then integrated into the BDT framework, in which uncertainty scenarios were incorporated to calculate the Expected Utility (EU) of each alternative and identify the optimal replacement strategy. The model was validated through expert review, consistency testing, sensitivity analysis, and internal mathematical verification. The proposed framework provides a systematic and objective approach to supporting pipeline replacement decisions by balancing technical, safety, operational, and economic considerations under conditions of uncertainty.

RESULTS AND DISCUSSION

Discussion of Research Results

The discussion of the results of this study is prepared to answer three main problem formulations, namely alternative methods for replacing underwater pipes that can be applied in the context of oil and gas operations, relevant multicriteria criteria for assessing alternative pipeline replacements, and how to integrate the results *of the Analytic Hierarchy Process* (AHP) and *Bayesian Decision Tree* (BDT) can be used to determine the most optimal decision alternative. Thus, this discussion not only explains the results of the calculation, but also relates the research findings to the theoretical basis that has been described in Chapter II, especially the theory of asset management, pipeline integrity management, multicriteria decision-making, AHP, BDT, and AHP-BDT integration.

Discussion of Alternative Methods of Replacing Underwater Pipelines in the Context of Oil and Gas Operations

Based on the results of the identification of alternative decisions, there are four alternative methods analyzed in this study, namely *Full Replacement*, *Segmented Replacement*, *Localized Repair*, and *Do Nothing*. These four alternatives are strategic choices that can be considered by oil and gas companies in determining actions against underwater pipelines that have experienced a decline in integrity. In the AHP model of research, alternative decisions are placed at the final level of the hierarchy, after the decision objectives and the five main criteria, namely Cost, HSSE, Technical, Flow Assurance, and Integrity. The alternatives used in such models are full replacement, partial replacement, local repair, and no replacement.

The Full Replacement alternative is a comprehensive pipeline replacement strategy. This alternative is considered the most comprehensive measure because it replaces the entire problematic pipeline with a new system. Based on Bayesian results, *Full Replacement* obtained a total successful utility of 81.70 and a failed utility of 39.40. The Expected Utility Prior value of 73.24 was adjusted to Expected Utility Posterior of 60.55 after the update of information through Bayesian update. Although the posterior value is lower than the prior value, Full Replacement remains the alternative with the highest EU Posterior value compared to the other alternatives. This shows that when new risk factors and evidence are incorporated into the model, Full Replacement still provides the greatest decision benefit, especially in terms of integrity, safety, and operational reliability.

Theoretically, these results are in line with the concept of pipeline integrity management and oil and gas infrastructure asset management. In Chapter II, it is explained that underwater pipelines are an important part of the offshore oil and gas production system because they function as a transportation route for hydrocarbon fluids from offshore facilities to processing facilities. In the event of a failure of the submarine pipeline, the impact is not only in the form of production disruptions, but can also include safety risks, environmental pollution, economic losses, and a decline in the company's reputation. Therefore, the choice of Full Replacement becomes rational if the condition of the pipeline has shown significant degradation and the risk of repeated failure.

Alternative Segmented Replacement is a replacement strategy for certain segments of the pipeline that are considered the most problematic. This alternative obtained a total successful utility of 79.55 and a failed utility of 36.30. The EU Prior value of 66.57 changed to the Posterior EU of 52.23 after the Bayesian update. This value puts Segmented Replacement in second place. These results show that this alternative still has a fairly good level of feasibility, mainly because it is able to reduce costs compared to Full Replacement, but still provide improved integrity in the most critical parts of the pipeline.

However, Segmented Replacement has the limitation of only partially replacing the pipeline. If the degradation has spread or the overall condition of the pipeline is unreliable, then partial replacement has the potential to leave a risk of failure in other segments that are not replaced. Therefore, this alternative is more suitable if the inspection results show that the damage is concentrated in a particular segment and that other parts of the pipe still have an adequate service life remaining.

Localized Repair Alternatives are local repair strategies at specific points, such as areas of heavy corrosion, connections, or locations that have leaked. This alternative results in a total successful utility of 74.90 and a failed utility of 32.40. The EU Prior value of 57.90 decreased to the EU Posterior of 43.99. The results put Localized Repair in third place.

Localized Repair has an advantage in terms of cost because it does not require extensive pipeline replacement. However, this alternative has a major drawback when applied to pipelines that have undergone systemic degradation. Local repairs only address visible or identified points of damage, while potential damage in other parts can still occur. Thus, this alternative is more appropriate to be used as a temporary solution or short-term mitigation measure, rather than as a primary strategy if the condition of the pipeline has shown a high integrity risk.

The Do Nothing alternative is the option of maintaining the existing condition without making significant replacements or repairs, in addition to intensive monitoring. This alternative obtained a total successful utility of 63.60 and a failed utility of 27.00. The EU Prior value of 37.98 decreased to the EU Posterior of 30.54. This value is the lowest of all the alternatives, making Do Nothing the least recommended.

Although Do Nothing has an upfront cost-advantage advantage because it does not require a large investment, this alternative poses a high risk to pipeline integrity, operational safety, potential leaks, environmental pollution, and production disruptions. In the context of asset management, the decision not to take action on critical assets that have undergone degradation can increase the risk of failure and the cost of losses in the future. Therefore, the results of the study show that the minimum cost approach does not always produce the best decisions, especially in underwater oil and gas assets that have a high-risk character.

Thus, the formulation of the first problem can be answered that alternative methods of subsea pipeline replacement that are possible to be applied in the context of oil and gas operations consist of Full Replacement, Segmented Replacement, Localized Repair, and Do Nothing. Based on the results of the analysis, Full Replacement is the most optimal alternative, followed by Segmented Replacement, Localized Repair, and Do Nothing.

Discussion of Relevant Multicriteria Criteria in the Alternative Assessment of Subsea Pipeline Replacement

This study uses five main criteria in the assessment of alternative underwater pipeline replacement, namely Integrity, Cost, Technical, HSSE, and Flow Assurance. These five criteria were chosen because the decision to replace the subsea pipeline is a complex decision that cannot be determined solely on the basis of cost. The decision must consider the physical reliability of the asset, operational safety, technical feasibility, production sustainability, and economic impact. In the research instrument, the criteria used to determine priority weights include Cost, HSSE, Technical, Flow Assurance, and Integrity.

Based on the results of the AHP, the Integrity criterion obtained the highest weight of 0.34 or 34%. This shows that the physical reliability, safety, and sustainability aspects of the system are the most dominant considerations in the decision to replace the submarine pipeline. In the results of the AHP normalization, Integrity also showed a dominant value in several columns, so that it became the criterion with the highest priority compared to other criteria.

The dominance of Integrity is understandable because underwater pipelines are critical assets that must operate safely and reliably in the long term. If the integrity of the pipeline decreases, the risk of leakage, operation failure, environmental pollution, and production downtime will increase. Therefore, the highest weight of Integrity shows that respondents or expert judgement emphasize the importance of the physical condition of the asset rather than just cost efficiency.

The Cost Criterion ranks second with a weight of 0.19 or 19%. This criterion relates to investment efficiency, project expenses, operational costs, and potential economic losses due to downtime or asset failure. These results suggest that the cost aspect remains important in decision-making, but is not a major factor. In the context of an undersea pipeline replacement project, a larger cost is acceptable if it can result in a significant improvement in integrity and risk reduction.

The Technical Criteria is in third place with a weight of 0.18 or 18%. These criteria describe technical feasibility, ease of implementation, complexity of workmanship, technological readiness, and alternative capabilities to be applied in oil and gas operational conditions. The high technical weight indicates that alternative pipeline replacement must be realistically feasible in the field. In other words, the best alternative is not only theoretically safe, but must also be feasible considering underwater conditions, existing facilities, contractor capabilities, and technical risks during construction.

The HSSE criteria obtained a weight of 0.16 or 16%. These criteria include health, occupational safety, security, and environmental aspects. In the offshore oil and gas industry, HSSE is an important aspect because pipeline failures can lead to oil spills, marine pollution, ecosystem disturbances, hazards to workers, as well as legal and reputational consequences. Although the weight of the HSSE is below Integrity, Cost, and Technicality, it still shows that safety and the environment are considerations that cannot be ignored.

The Flow Assurance criteria obtained the lowest weight of 0.13 or 13%. Flow Assurance is concerned with the smooth flow of fluids, pipeline operability, potential flow resistance, and production sustainability after replacement is performed. The lower weighting does not mean that Flow Assurance is not important, but it does indicate that in the context of this case, respondents prioritized the physical reliability of the pipeline and risk control. The AHP results also explain that Flow tends to be seen as a supporting factor, rather than a major factor, although it still affects the overall efficiency and performance of the system.

If associated with the Multi-Criteria Decision Making (MCDM) theory in Chapter II, the use of these five criteria is appropriate because MCDM is used to help decision-makers evaluate several alternatives based on more than one criterion. In the case of subsea pipeline replacement, the criteria used have different and interrelated characters. Cost represents the economic aspect, HSSE represents the safety and environmental aspect, Technical represents the feasibility aspect of implementation, Flow Assurance represents the aspect of smooth operation, while Integrity represents the reliability of the asset.

Thus, the formulation of the second problem can be answered that the relevant multicriteria criteria in the assessment of subsea pipeline replacement alternatives are Integrity, Cost, Technical, HSSE, and Flow Assurance. The weighting results show that Integrity is the most dominant criterion, while other criteria still serve as a counterweight so that the resulting decisions are not only oriented to one aspect.

Discussion of the Integration of AHP and Bayesian Decision Tree in the Selection of Optimal Alternatives

The integration of AHP and BDT in this study was carried out to produce a more comprehensive decision-making model. AHP is used to determine the priority weight of criteria based on expert judgment, while BDT is used to process the weight along with the probability of success and failure scenarios, resulting in an Expected Utility value for each alternative. In the study, it was explained that AHP was used to determine the weights of the five main criteria, while BDT was used to process those weights along with historical failure probability data and information updates through posterior updating.

Conceptually, this integration is important because AHP and BDT have different but complementary functions. AHP is strong in capturing decision-makers' preferences for qualitative and strategic criteria. However, AHP has limitations in capturing probabilistic risk dynamics. In contrast, BDT is able to model uncertainty through scenario probability and expected utility calculations, but requires a preference structure or criterion weighting to keep decision results reflective of managerial priorities. Therefore, the integration of AHP-BDT is able to produce more objective, transparent, and adaptive decisions against uncertainty.

In this study, the weight of the AHP results was used as the basis for calculating the utility of each alternative. Because Integrity has the highest weight, alternatives that have high performance in terms of integrity will have greater utility value. This can be seen in Full Replacement, where the successful utility contribution to Integrity reaches 30.60. This value is higher than Integrity's contribution to Segmented Replacement, Localized Repair, and Do Nothing. Thus, the weight of the AHP plays a direct role in shaping the utility value of each alternative.

The BDT results show that all alternatives have decreased in value from EU Prior to EU Posterior after Bayesian updates. Full Replacement decreased from 73.24 to 60.55; Segmented Replacement decreased from 66.57 to 52.23; Localized Repair decreased from 57.90 to 43.99; and Do Nothing fell from 37.98 to 30.54. This decline suggests that when new information or evidence of risk is incorporated into the model, utility values become more realistic because they have taken into account the possibility of failure and operational uncertainty.

Despite the decline, Full Replacement still has the highest EU Posterior value. This suggests that the alternative is most powerful overall, both before and after the probability update. In other words, Full Replacement not only excels based on initial preferences, but also remains superior after new risks and evidence are taken into account. This condition reinforces the recommendation that Full Replacement is the most optimal alternative for subsea pipeline replacement cases that have a high degree of degradation and risk of failure.

Segmented Replacement occupies the second position with EU Posterior at 52.23. This alternative shows a balance between cost efficiency and improved integrity. However, because it only replaces certain segments, the risk of failure in other parts of the pipe is still possible. Therefore, Segmented Replacement can be an alternative if budget constraints are the main consideration and the overall condition of the pipeline is still acceptable.

Localized Repair took third place with EU Posterior at 43.99. This alternative is suitable for damage conditions that are local and have not spread. However, if the pipe has shown repeated degradation, Localized Repair is less able to provide a long-term solution. This can be seen from the lower EU Posterior values compared to Full Replacement and Segmented Replacement.

Do Nothing gained the lowest EU Posterior value of 30.54. These results suggest that a no-replacement strategy is not a viable option for the case of subsea pipelines that have a high integrity risk. Although the initial cost is low, the risk of failure, HSSE risk, and potential operational disruption make this alternative not optimal. Thus, the integration of AHP-BDT is able to show that decisions that appear to be cost-effective in the short term can be an inappropriate choice when analyzed based on risk and expected utility.

The following table can be used to clarify the final result of alternative rankings:

Table 1. Alternative Ranking Results

Ranking	Alternative	EU Prior	Posterior SELF	Interpretation
1	Full Replacement	73,24	60,55	The most optimal alternative as it provides the best reliability and risk control
2	Segmented Replacement	66,57	52,23	The second alternative, which is more efficient but still leaves risks in other segments
3	Localized Repair	57,9	43,99	Suitable for local damage, but less than optimal for thorough degradation
4	Do Nothing	37,98	30,54	Not recommended due to the highest integrity and safety risks

Source: Author's calculation based on AHP–BDT integration using expert judgment and project data from PT PHE OSES (2024–2025)

Thus, the formulation of the third problem can be answered that the integration of AHP and BDT can be used to select an alternative method of optimal subsea pipeline replacement by combining the priority weight of the criteria and the probability of the decision scenario. AHP provides a weighting structure based on expert judgement, while BDT provides probabilistic evaluation based on expected utility. The results of the integration show that Full Replacement is the best alternative for oil and gas companies because it has the highest EU Posterior.

Synthesis of Discussion on the Formulation of Research Problems

Based on all the results of the analysis, this study was able to answer all three problem formulations systematically. First, alternative methods of replacing underwater pipelines that can be applied in the context of oil and gas operations are Full Replacement, Segmented Replacement, Localized Repair, and Do Nothing. The four alternatives represent a spectrum of decisions from the most comprehensive action to the least action.

Second, the relevant multi-criteria criteria for assessing subsea pipeline replacement alternatives are Integrity, Cost, Technical, HSSE, and Flow Assurance. The results of the AHP weighting show that Integrity is a top priority, which means that the decision to replace the subsea pipeline places more emphasis on asset reliability, safety, and sustainability of operations than cost efficiency alone.

Third, the integration of AHP and BDT has proven to be able to produce a more objective and measurable decision-making process. AHP helps prioritize criteria based on expert judgment, while BDT helps account for risk and uncertainty through Expected Utility values. The final results show that Full Replacement has the highest EU Posterior value, so it is recommended as an optimal alternative.

Overall, the results of this study confirm that the replacement of subsea pipelines cannot be viewed as just an investment decision, but must be understood as a strategic decision in oil and gas asset management. A good decision must be able to balance cost, technical feasibility, safety, smooth operation, and asset integrity. Therefore, the AHP-BDT integrative model can be used as a relevant decision-making framework for oil and gas companies in determining strategies for replacing underwater pipelines in a more comprehensive, transparent, and data-based manner.

CONCLUSION

Four subsea pipeline intervention alternatives were identified as applicable to the operational context of the oil and gas industry: Full Replacement, Segmented Replacement, Localized Repair, and Do Nothing. These alternatives represent a range of strategies, from complete pipeline replacement and partial segment replacement to localized repairs at critical locations and continued operation without replacement. The Bayesian Decision Tree (BDT) analysis showed that Full Replacement was the optimal alternative, achieving the highest posterior Expected Utility (EU) value of 60.55, followed by Segmented Replacement (52.23), Localized Repair (43.99), and Do Nothing (30.54). These findings indicate that Full Replacement provides the greatest overall benefit in terms of asset reliability, risk mitigation, and long-term operational sustainability.

The evaluation of the subsea pipeline replacement alternatives was based on five decision criteria: Integrity, Cost, Technical, Health, Safety, Security, and Environment (HSSE), and Flow Assurance. These criteria were selected because subsea pipeline replacement decisions require balancing asset reliability, operational continuity, technical feasibility, safety, environmental protection, and economic considerations. The Analytic Hierarchy Process (AHP) results showed that Integrity received the highest priority weight of 0.34 (34%), making it the most influential criterion in the decision-making process, followed by Cost at 0.19 (19%), Technical at 0.18 (18%), HSSE at 0.16 (16%), and Flow Assurance at 0.13 (13%). These results indicate that pipeline replacement decisions prioritize long-term asset integrity while also considering economic efficiency, technical feasibility, operational performance, and safety.

The integration of the Analytic Hierarchy Process (AHP) and the Bayesian Decision Tree (BDT) provided a robust framework for selecting the optimal subsea pipeline replacement strategy by combining expert-based criteria weighting with probabilistic decision analysis. Within this framework, AHP established the relative importance of each evaluation criterion, whereas BDT estimated the posterior Expected Utility (EU) of each alternative by incorporating uncertainty, success and failure scenarios, and Bayesian updating. The integrated analysis confirmed that Full Replacement, with the highest posterior EU value of 60.55, was the preferred alternative because it offered the greatest potential to maintain pipeline integrity, reduce failure risk, enhance operational safety, and ensure production continuity. Conversely, the Do Nothing alternative, with the lowest posterior EU value of 30.54, was not recommended because of its substantially higher integrity, safety, and operational risks. Overall, these findings demonstrate that the integrated AHP–BDT framework provides a more objective, transparent, and evidence-based decision-making approach for evaluating subsea pipeline replacement alternatives by simultaneously incorporating expert judgment, probabilistic risk assessment, and the expected utility of each decision.

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