Article

Influence-Based Consequence Assessment of Subsea Pipeline Failure under Stochastic Degradation

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Abstract: The complexity of corrosion mechanisms in harsh offshore environments poses safety and integrity challenges to oil and gas operations. Exploring the unstable interactions and complex mechanisms required an advanced probabilistic model. The current study presents the development of a probabilistic approach for a consequence-based assessment of subsea pipelines exposed to complex corrosion mechanisms. The Bayesian Probabilistic Network (BPN) is applied to structurally learn the propagation and interactions among under-deposit corrosion and microbial corrosion for the failure state prediction of the asset. A two-step consequences analysis is inferred from the failure state to establish the failure impact on the environment, lives, and economic losses. The essence is to understand how the interactions between the under-deposit and microbial corrosion mechanisms' nodes influence the likely number of spills on the environment. The associated cost of failure consequences is predicted using the expected utility decision theory. The proposed approach is tested on a corroding subsea pipeline (API X60) to predict the degree of impact of the failed state on the asset's likely consequences. At the worst degradation state, the failure consequence expected utility gives 1.0822×10^8 USD. The influence-based model provides a prognostic tool for proactive integrity management planning for subsea systems exposed to stochastic degradation in harsh offshore environments.

Keywords: subsea pipeline; under-deposit corrosion; influential risk factors; Bayesian probabilistic network; microbial corrosion; expected utility decision theory

1. Introduction

Critical subsea facilities are exposed to harsh operating environments. These harsh environmental factors have a multi-dimensional impact on the integrity and sustainability of the oil and gas infrastructures, especially in harsh Arctic operations. For instance, the subsea flowlines, such as risers, umbilicals, etc., are exposed to different degradation potentials that could result in failure with catastrophic consequences on the environment, lives, and the company's reputation. Recent advances in material enhancements geared toward promoting system reliability and sustainability in harsh offshore operations are shown in

the literature [1–3]. Some advanced technology adopts stainless steel applications with high Pitting Resistance Equivalent Number (PREN) and nanotechnology [4–6]. Nevertheless, due to complex degradation influential factors in the marine environment and material formation uncertainty, these systems are still vulnerable to a high rate of deterioration in offshore oil field operations [7]. For example, temperature, pressure, biofouling, salinity, water/fluid velocity, salt, chloride, suspended solids, carbon dioxide, bacteria, material composition, and surface roughness present different facilitating potentials in corrosion susceptibility of subsea systems. The rate of system susceptibility increases under complex interactions among these influential parameters.

Moreover, the under-deposit formation and the microbial metabolism complicate the complexity of the degradation process of the steel structures. The characteristics feature of the microorganism, such as bacteria, algae, protozoa, and fungi, promote their coexistence and survivability even in a harsh environment. They exist in the colony through the fusion of their cells and Extracellular Polymeric Substances (EPS), e.g., polysaccharides [8,9]. The EPS provides a supportive environment that promotes metabolism, growth, and sustainability. This formation sustains the degradation potential of the microorganism on the steel structural integrity. The under-deposit, as a result of debris and suspended particles, also provides a support spot for microbial and under-deposit corrosion. This kind of support system produces a complicated array of dynamic corrosive microenvironments that instigate steel degradation [10–12].

Biofilm formation begins with the adsorption of organics to the steel surface in the form of a conditioning layer. As the conditions of the system change, secondary colonizers utilize the film as a substrate for growth and metabolism. The process of initial bacteria attachment to the steel surface is described by the reversible adsorption process based on electrostatic attraction and physical forces [13]. The adhesion formation process gradually developed into an irreversible adhesion [14]. Several approaches to understanding the bacteria adhesion process to steel surfaces have been reported in the literature [13,15,16]. For instance, Absolom et al. [15] applied the concept of short-range interaction force to observe the point of direct bacteria contact with the substratum and interfacial tension based on the Gibbs free energy. It was observed that the hydrophobicity of the substrate enhances microbial cell adhesion to the surfaces. Tran et al. [16] studied the bacteria adhesion to different stainless steels and their corrosion behavior in artificial seawater. There is a limited study that explores the combined effect of bacteria adhesion influential factors and under-deposit impact on biofilm formation and the corrosion mechanism of subsea components, especially subsea pipelines. The complex multispecies biofilm may create a nutrient support ecosystem in the offshore pipeline during operations. These factors play an influential role in the failure of the subsea system and the likely consequences on the marine ecosystem and species sustainability. In this circumstance, therefore, there is a need to capture these influential factors for risk-informed decision making through the development of a probabilistic network-based failure consequences framework for harsh offshore operations.

The current study presents the development of an influence-based Bayesian Probabilistic Network (BPN) for consequence assessment of subsea pipelines suffering under-deposit and microbial-induced degradation. The model offers a novel inferential formalism that captures the predisposing factors and their deteriorating potential to establish a temporal degradation profile for the subsea system and predict the environmental impact of the failure of the asset. Furthermore, a decision-based theory is integrated to predict the economic loss due to the ecological impact and operational downtime due to pipeline failure. The model is tested with a subsea pipeline exposed to stochastic degradation. The results show the applicability of the model, capturing complex interactions of key influential factors on the degradation, failure potential, and the economic consequence of the pipeline failure.

The remaining sections of the paper are structured as follows: Section 2 presents an overview of the subsea component under stochastic degradation. Section 3 briefly describes

the consequences assessment approach and its application. Section 4 provides the results and discussion, and Section 5 concludes the paper.

2. Overview of Subsea Component under Stochastic Degradation

The microenvironment created by the supporting nutrient promotes the corrosion of the pipeline. For instance, the process of oxygen consumption, which is a cathodic reactant in the aerobic corrosion phase, is instigated by the aerobic microorganisms that cause concentration shifts resulting in pitting corrosion of the steel pipe. Moreover, in the multispecies biofilm architecture, the aerobic and the anaerobic bacteria co-exist in a synergistic relationship that protects them from the harsh environment. As the aerobic bacteria (Iron oxidizing bacteria-IOB, etc.) use oxygen for their growth, their metabolic by-product becomes a substrate or energy source for the anaerobic bacteria. The synergistic relationship within the biofilm complicates the corrosion mechanism modeling [8]. For consequence assessment, there is no comprehensive understanding of the influential parameters' concentration effects on the biofilm formation and its failure-induced characteristic of the pipeline. Additionally, their by-product, such as H_2S, is corrosive and enhances the steel pipeline's corrosion propagation. Moreover, surface deposits provide a sheltering potential for the bacteria metabolism, giving rise to channeling corrosion mechanisms [17]. This corrosion type is severe and complicated, with limited understanding of its mechanisms [12]. The offshore facilities are exposed to this complex degradation mechanism, which results in an unpredictable failure and pollution of the marine environment. Several methods that examined material susceptibility modeling have been explored by researchers, as demonstrated in the literature [18–21]. Nevertheless, the instability and complexity of the influential parameters require a probabilistic approach. The essence is to capture the time-changing behaviors of environmental and operational key factors and the heterogeneous characteristics of the bacteria colony for real case consequence modeling.

Research has shown that the degradation of the offshore pipeline under complex corrosion mechanisms can be modeled using probabilistic techniques [22–25]. For instance, Xie et al. [25] proposed a physic-based multi-state Markovian approach for pipeline corrosion prediction under a chloride-containing environment. Adumene et al. [22] demonstrate the application of Markov mixture techniques to capture the interaction among multiple defects on the failure characteristics of the pipeline. Taleb-Berrouane et al. [24] proposed a Bayesian network-based susceptibility model for the offshore pipeline under complex corrosion mechanisms. The model adopts an influential-based formalism to define the degree of impact, the key factors of microbial corrosion, and their failure-induced potentials. The reviewed approaches show the potency of probabilistic techniques for susceptibility prediction in offshore operations. However, the models did not explore the consequences of the system failure under the complex corrosion mechanisms, especially for a joint under-deposit and microbial corrosion scenario. The ecological devastation due to corrosion-induced failure has not been comprehensively explored. The present approach explores the influential factors' impact and their propagation to build a novel network-based consequence assessment framework for the subsea pipeline.

3. Consequence Assessment Approach and Application

This section outlines the steps adopted in forming the influence-based consequences assessment framework for offshore systems under complex corrosion mechanisms. The following explores the steps for the proposed network-based structure.

Step 1. The proposed framework begins by defining the system, its material composition, and the operating environments, as detailed in the work of Adumene et al. [22]. This is followed by understanding the environmental, operational factors, and bacteria features and their impact on corrosion propagation.

Step 2. In this step, the influential factors' characteristics are examined to establish a structural relationship among them and their effect on the degree of susceptibility of the subsea system to degradation. Structural learning helps to understand the propagation

pathway and its conditional dependencies. This is defined by the physics/mechanics of the processor by experience from subject matter experts. At this stage, the intermediate nodes are extracted based on the structural learning of the interactions among the influential parameters. The essence is to reduce structural complexity during the modeling of the network.

Step 3. Based on the established knowledge of the structural interactions of the influential factors from step 2, the Bayesian Probabilistic Network (BPN) is applied to build the structure. The BPN is a reliable modeling technique that captures multi-dimensional influences of the key failure-induced factors to simultaneously predict the corrosion propagation and the consequences of failure of the offshore system. It offers an advantage for multivariate data integrated platform, especially under multiple data sources. Its merits and applicability for stochastic degradation modeling are detailed in the referenced literature [18,22,26]. The BPN presents flexibility to combine both continuous and discrete nodes for predictive analysis, able to use both conditionally deterministic functions and statistical distribution [27,28].

For a random set of operating variables $U = \{Y_1, \ldots\ldots, Y_n\}$, the conditional independence is mathematically represented by Equation (1) based on the chain rule and joint probability distribution $P(U)$ [29]: Hence,

$$P(U) = \prod_{i=1}^{n} P(Y_i | P_y(Y_i))$$
(1)

where $P_y(y_i)$ introduces the parent of variable Y_i and $P(U)$ refers to the joint probability distribution of the variables. The probability of Y_i is calculated as follows:

$$P(Y_i) = \sum_{U \setminus Y_i} P(U)$$
(2)

where the summation is taken over all the variables except Y_i..

The Bayes' theorem is used to estimate the posterior of the event upon the availability of new information (called evidence E), as shown in Equation (3).

$$P(U|E) = \frac{P(U, E)}{P(E)} = \frac{P(U, E)}{\sum_U P(U, E)}$$
(3)

The expected unity of the failure event called A is defined as

$$EU(A) = \sum_{o \in O} P_A(o) U(o)$$
(4)

where O is the set of outcomes, $P_A(o)$ is the probability of outcome o conditional on A, and $U(o)$ is the utility of o. The expected utility decision theory is inbuilt into the BN software.

Based on prior knowledge, the basic causative/predisposing factors to microbial corrosion and under-deposit corrosion are used. The intermediate node is built assuming the same propagating influence as presented in our previous works [7,18]. The causative impact is propagated through the intermediate nodes to the failure node and uses the failure information to define the decision node and its characteristics, as shown in Figure 1. The state of material degradation is defined as "High", "Moderate", and "Low", respectively, while the failure state is categorized as "leak" and "Noleak". The BN captures both vertical and horizontal dependencies based on the structural learning of the study phenomenon. It is important to note that the framework in Figure 1 is applicable to oil and gas pipelines. However, in this study, an oil transmission pipeline is used as a test case study.
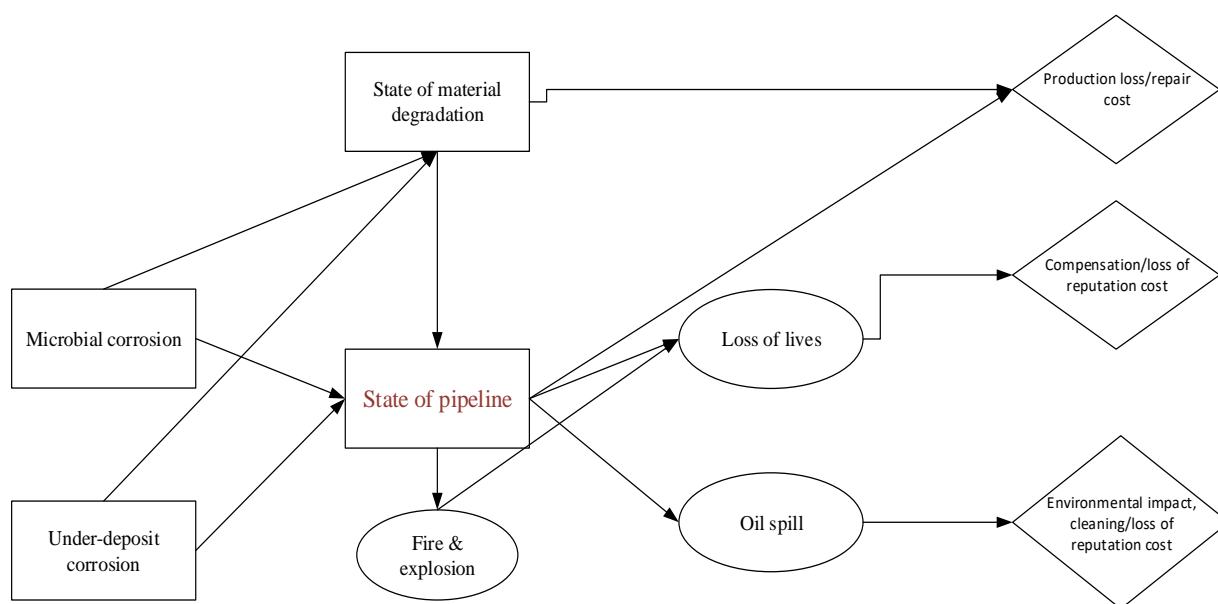
Figure 1. An influence-based framework for consequence assessment due to stochastic degradation.

For this study, the states in the nodes are defined as "present" and "absent" for the microbial and under-deposit corrosion node. Two-step consequences of failure are considered in this case where the state of the asset is used to define the possibility of a shutdown node, followed by the oil spill/gas release node and loss of lives node due to explosion or fire for gas pipeline. The state of oil spill can be categorized based on the volume of spill and the environmental impact, such as "No oil spill", "Minor oil spill (<10,000 barrels)", "Major oil spill (10,000–200,000 barrels)", and "Catastrophic oil spill (>200,000 barrels)". While if it is a gas pipeline the gas release node states are defined as "Yes" and "No". The specific outcomes could therefore be defined based on the study scenario. For detailed information on the formulations guiding the BPN modeling and the utility decision theory, readers are referred to the referenced literature [7,30,31].

In Step 4, a decision-making process based on sensitivity analysis is used to establish the degree of impact of the failed state on the second level consequence in terms of economic loss. This provides response-based information inferred from the intermediate nodes and the failure state of the asset for proactive integrity management planning. The proposed influenced-based probabilistic model presents an adaptive approach for two-step consequence analysis for systems that are exposed to stochastic degradation.

The proposed approach is tested on a 2 km crude oil transmission pipeline (API X60) with a 762 mm outer diameter operating in a harsh offshore environment [7,32,33]. Upon investigation, severe localized defects at the 6 o'clock position of the pipe section were observed as a result of exposure to under deposit-based microbial corrosion with a complicated failure instigating mechanism. The pipeline has been under a corrosion management procedure with an oil corrosion inhibitor dose of 4.70 ppm. The failure of the corrosion management practice and low fluid velocity supported the particles' deposition and microbial metabolism. This enhances the pipeline degradation process. To simplify the analysis, the intermediate nodes indicating the under-deposit and microbial corrosion are used to simulate the degradation propagation to the failed state, defined as "Leak" and "NoLeak". The consequence of failure is then simulated following a two-step approach for optimum decision-making. The baseline costs for the financial losses associated with the failure scenarios are extracted from the reference literature [27,34–36]. The proposed approach's computational time depends on the complexity of the study scenarios and model structure. For the study case, a 32 GB 64-bit operating system computer, dual core i7, 2.20–2.90 GHz, was used with an average computational time of 2.03 ± 1.12 s.

4. Results and Discussions

The current study develops an influenced-based probabilistic model for the consequences assessment of subsea pipelines suffering stochastic degradation. The Bayesian Probabilistic Network is built, connecting the intermediate nodes, i.e., microbial corrosion and under-deposit corrosion, to the failure state of the asset, considering their dependencies. The state of failure is propagated to predict the two-step consequences, as shown in Figure 2. Figure 2 shows the parametric learning of the proposed structure for an offshore oil transmission pipeline exposed to microbial and under-deposit corrosion. At the 87% likelihood of leak failure, given the prevailing operating conditions of the asset, the predicted economic losses based on the expected utility nodes are 1.640×10^7 USD and 9.379×10^7 USD for the production loss/repair cost and cost of environmental impact, cleaning up, and loss of reputation, respectively. The economic costs for environmental impact capture the cost of natural resources damage and their restoration from a moderate spill. This is benchmarked after the work of [36]. As predicted based on the utility theory, the economic cost depends on the likelihood of occurrence, as shown in the BPN structure and the volume of the spill. Several endangered species may suffer extinction due to oil spill toxicity.
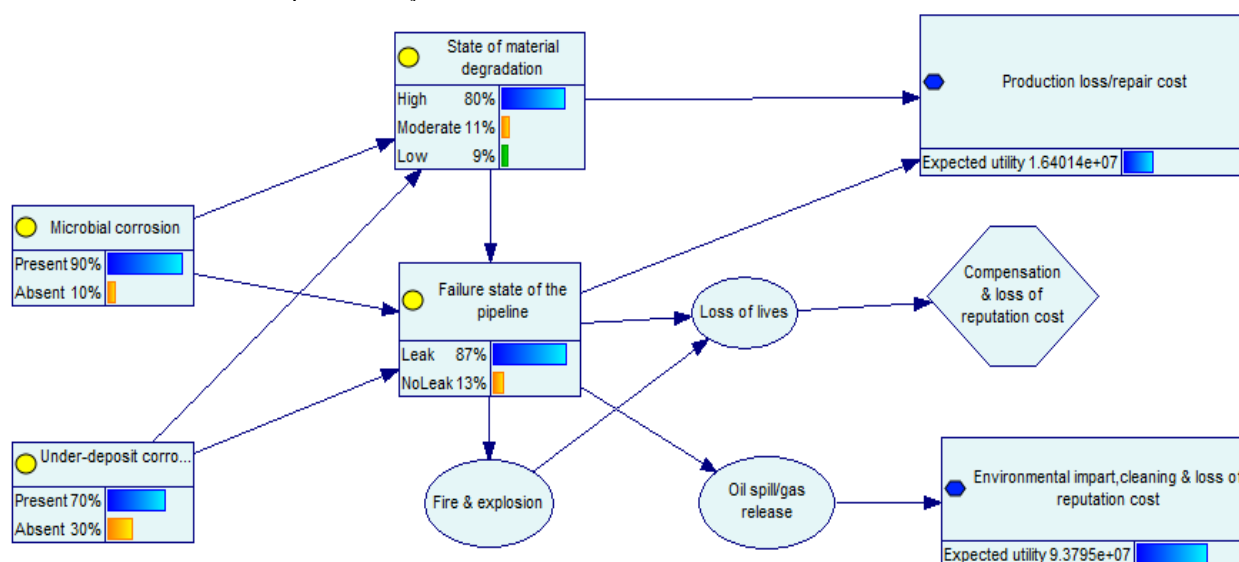

Figure 2. Parametric learning of the BPN model for economic loss prediction.

To further assess the impact of interactions among the corrosion types on the expected utility in USD, evidence is placed on the microbial corrosion and under-deposit corrosion nodes, as shown in Figure 3. The result shows the effect on the rate of material degradation and an 8.1% increase in the likelihood of leak failure. This increase in the state of degradation and failure induced a multiplier effect on the economic costs for the production loss/repair cost and environmental cost, cleaning up, and loss of reputation cost. The result indicates an increase in economic loss based on the expected utility by 6.3% and 8.2% for the production loss/repair cost, environmental cost, cleaning up, and loss of reputation cost. As the belief is assertive on the corrosion nodes and the high rate of material deterioration, the likelihood of system failure increases with corresponding consequences on the environment and financial losses on the investment. Further sensitivity investigation shows that with this assertion, the economic loss due to environmental impact, clean-up, and loss of reputation increases by 9.1%, as shown in Figure 4. The result indicates that there is a 95% likelihood of leak failure happening at this point, and the expected utility is predicted based on a moderate spill benchmark. The essence is to understand the progressive impact of the state of failure on the predicted two-step consequences in terms of economic costs to aid decision-making. This provides initial validation for the proposed model. There is a need to understand the comparative cost advantages in this context in order to optimize safety

barriers/measures that can limit the propagation of failure upon exposure of the asset to complex corrosion mechanisms. The summary of the parametric and evidence-based analysis of the corrosion states propagation is shown in Table 1.
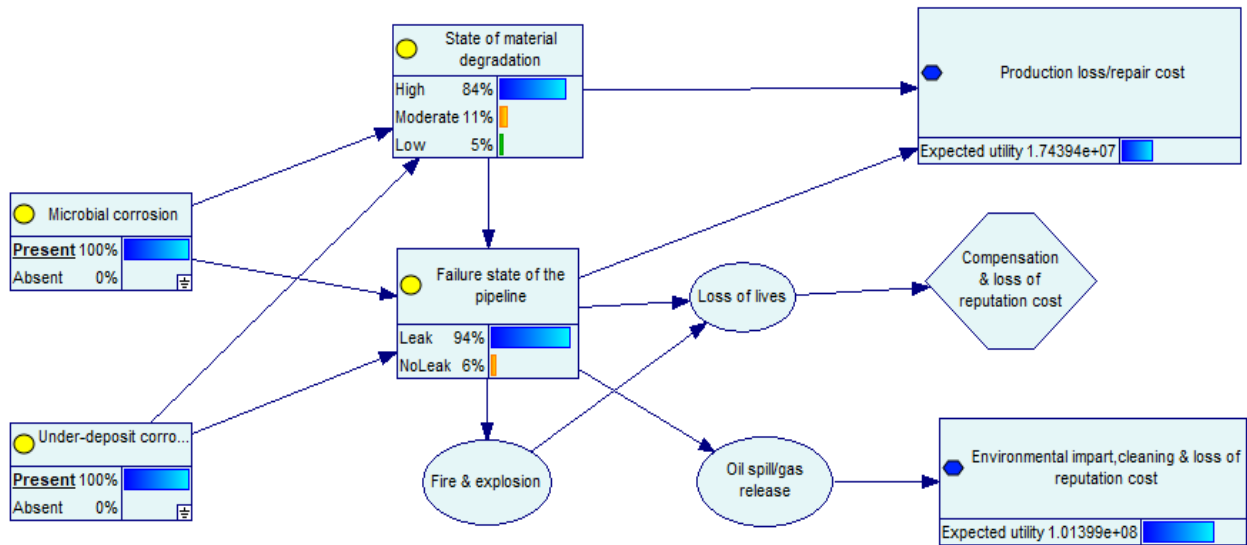

Figure 3. Impact of evidence on the corrosion nodes on the predicted economic losses.
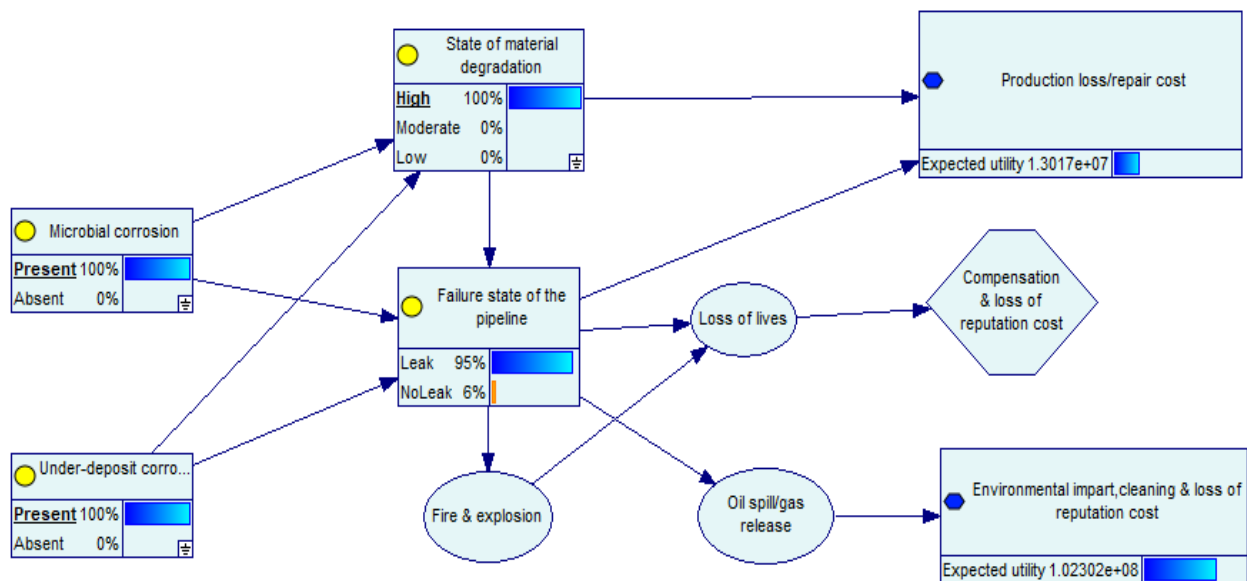

Figure 4. Impact of complex interaction on the failure state and the predicted economic losses.

The propagation of the effect of complex interactions and the high rate of material deterioration affects the health state of the asset, as demonstrated. To further ascertain the impact when catastrophic leak failure has occurred, evidence is placed on the leak state of the failure node of the pipeline, as shown in Figure 5. The result shows a progressive increase in the economic costs due to natural resources damage and restoration, cleaning up, and loss of reputation. In this case, the leak failure is assumed to be catastrophic with a long-term impact on the marine ecosystem and species conservation. It is important to note that there may be variability in the expected utility because of the instability in the failure of influential factors of the asset and the BPN nodes' state probabilities. The variation is dependent on the system's operating terrain and the market influencing factors. The expected utility-based prediction provides hands-on information for decision-making processes, especially for the safe operation of critical subsea infrastructures in harsh

environments. A proactive integrity management option can be explored based on the results of the proposed approach.

Table 1. Results of the parametric learning and evidence-based analysis of the case study.

| Corrosion State		State of Degradation			Failure State Probability		Consequence States		
Type	Probability	High	Moderate	Low	Leak	NoLeak	Production Loss/Repair Cost (USD)	Compensation and Loss of Reputation Cost (USD)	Environmental Impacts (USD)
Microbial	0.899	0.796	0.111	0.093	0.866	0.134	1.64×10^7	1.19×10^5	9.38×10^7
Under-deposit	0.701								
Microbial	1	0.837	0.109	0.037	0.937	0.063	1.74×10^7	1.22×10^5	1.01×10^8
Under-deposit	1								
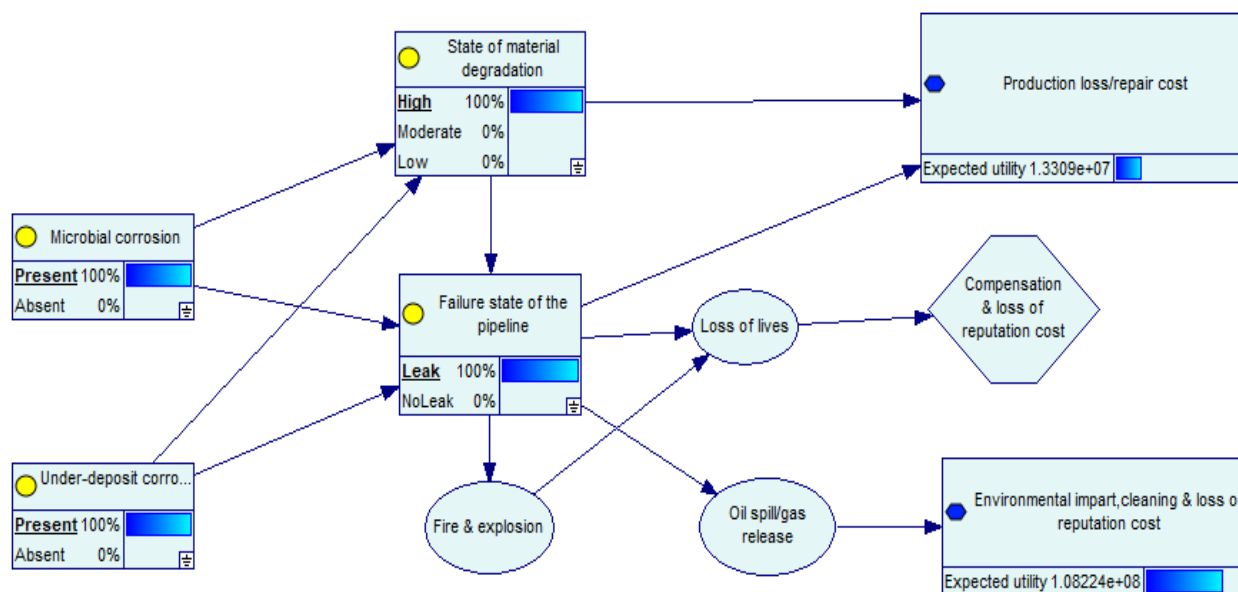
Figure 5. Evidence of leak failure on the predicted economic losses.

The current study provides a novel influence-based assessment tool that will aid system operators and integrity managers in proactive mitigation planning against failure in harsh offshore operations. However, the associated subjectivity with the prior and posterior probability estimation in BPN could be a limitation.

5. Conclusions

The current study presents an adaptive probabilistic tool for consequences-based assessment due to the corrosion-induced failure of a subsea pipeline. The complex mixed corrosion mechanism influences the degradation of the asset in harsh offshore operations. The model adopted the BPN to explore the interactions among these corrosion mechanisms and the state of material degradation. The assessment considers a two-level consequence analysis induced by stochastic degradation and updates the asset's failure state and its propagation. The model test shows its adaptiveness and applicability to economically predict the failure-induced impact on the marine environment and the financial losses. The following are key findings of the current study.

- The proposed model structure is adaptive, able to explore the unstable characteristics of the corrosion propagation on the failure state of the pipeline
- The model captures the interaction among the microbial and under-deposit corrosion mechanisms that have explored the likelihood of leak failure and its influence on the consequences.

- The expected utility decision theory reliably predicted the economic costs of failure given different degrees of interactions among the influential factors.
- The result shows that at the 87% likelihood of leak failure, the expected utility gives 1.640×10^7 USD and 9.379×10^7 USD. This accounted for moderate oil spills with environmental consequences
- At 100% leak failure, the economic loss due to natural resources damage and restoration, cleaning up, and loss of reputation increases by 9.1%. This represents a catastrophic oil spill with devastating impacts on the marine ecosystem and species conservation.
- The current approach offers a hands-on consequence-based prediction tool for integrity management considering stochastic degradation in harsh offshore environments.

The proposed model offers a novel probabilistic influenced-based model for failure consequence assessment under uncertainty. However, the approach can be integrated with copula-based modeling capturing the nonlinear correlation among economic risk influencing factors. This will be considered in our future work.

References

1. Albu, M.; Panzirsch, B.; Schröttner, H.; Mitsche, S.; Reichmann, K.; Poletti, M.C.; Kothleitner, G. High-resolution microstructure characterization of additively manufactured x5crnicunb17-4 maraging steel during ex and in situ thermal treatment. *Materials* **2021**, *14*, 7784. [CrossRef] [PubMed]
2. Cross, J.; Opila, R.; Boyd, I.; Kaufmann, E. Materials characterization and the evolution of materials. *MRS Bull.* **2015**, *40*, 1019–1033. [CrossRef]
3. Shifler, D.A. Understanding material interactions in marine environments to promote extended structural life. *Corros. Sci.* **2005**, *47*, 2335–2352. [CrossRef]
4. Adumene, S.; Ikue-John, H. Offshore systems' safety and operational challenges in harsh Arctic operations. *J. Saf. Sci. Resil.* **2022**, *3*, 153–168. [CrossRef]
5. Chauhan, D.S.; Quraishi, M.A.; Mazumder, M.A.J.; Ali, S.A.; Aljeaban, N.A.; Alharbi, B.G. Design and synthesis of a novel corrosion inhibitor embedded with quaternary ammonium, amide and amine motifs for protection of carbon steel in 1 M HCl. *J. Mol. Liq.* **2020**, *317*, 113917. [CrossRef]
6. Handoko, W.; Pahlevani, F.; Sahajwalla, V. Enhancing corrosion resistance and hardness properties of carbon steel through modification of microstructure. *Materials* **2018**, *11*, 2404. [CrossRef]
7. Adumene, S.; Khan, F.; Adedigba, S.; Zendehboudi, S. Offshore system safety and reliability considering microbial influenced multiple failure modes and their interdependencies. *Reliab. Eng. Syst. Saf.* **2021**, *215*, 107862. [CrossRef]
8. Kadwa, U. A Study on Biofilm Formation in Pipelines (Issue March). Master's Thesis, University of KwaZulu-Natal, Durban, South Africa, 2015.
9. Machuca, L.L. Microbiologically influenced corrosion: A review focused on hydrotest fluids in subsea pipelines. *Corros. Prev.* **2014**, 117.
10. Chang, Y.-C.; Woollam, R.C.; Orazem, M. Mathematical Models for Under-Deposit Corrosion. *J. Electrochem. Soc.* **2014**, *161*, C321–C329. [CrossRef]
11. de Carvalho, C.C.C.R. Marine Biofilms: A Successful Microbial Strategy With Economic Implications. *Front. Mar. Sci.* **2018**, *5*, 126. [CrossRef]
12. Wang, X.; Melchers, R.E. Long-term under-deposit pitting corrosion of carbon steel pipes. *Ocean Eng.* **2017**, *133*, 231–243. [CrossRef]
13. Zhang, Y.; Ge, H.; Lin, W.; Song, Y.; Ge, F.; Huang, X.; Meng, X. Effect of different disinfection treatments on the adhesion and separation of biofilm on stainless steel surface. *Water Sci. Technol.* **2021**, *83*, 877–885. [CrossRef] [PubMed]
14. Grzegorczyk, M.; Pogorzelski, S.J.; Pospiech, A.; Boniewicz-Szmyt, K. Monitoring of marine biofilm formation dynamics at submerged solid surfaces with multitechnique sensors. *Front. Mar. Sci.* **2018**, *5*, 363. [CrossRef]
15. Absolom, D.R.; Lamberti, F.V.; Policova, Z.; Zingg, W.; van Oss, C.J.; Neumann, A.W. Surface thermodynamics of bacterial adhesion. *Appl. Environ. Microbiol.* **1983**, *46*, 90–97. [CrossRef] [PubMed]

16. Tran, T.T.T.; Kannoorpatti, K.; Padovan, A.; Thennadil, S. A study of bacteria adhesion and microbial corrosion on different stainless steels in environment containing Desulfovibrio vulgaris. *R. Soc. Open Sci.* **2021**, *8*, 201577. [CrossRef] [PubMed]

17. Huang, J. *Mechanistic Study of Under Deposit Corrosion of Mild Steel in Aqueous Carbon Dioxide Solution*; Ohio University: Athens, OH, USA, 2013; Issue December. [CrossRef]

18. Adumene, S.; Khan, F.; Adedigba, S.; Zendehboudi, S.; Shiri, H. Offshore pipeline integrity assessment considering material and parametric uncertainty. *J. Pipeline Sci. Eng.* **2021**, *1*, 265–276. [CrossRef]

19. Huang, R.T.; McFarland, B.L.; Hodgman, R.Z. Microbial Influenced Corrosion in Cargo Oil Tanks of Crude Oil Tankers. *NACE Int. Corros. Conf.* **1997**, 535.

20. Liu, H.; Cheng, Y.F. Mechanistic aspects of microbially influenced corrosion of X52 pipeline steel in a thin layer of soil solution containing sulphate-reducing bacteria under various gassing conditions. *Corros. Sci.* **2018**, *133*, 178–189. [CrossRef]

21. Marciales, A.; Peralta, Y.; Haile, T.; Crosby, T.; Wolodko, J. Mechanistic microbiologically influenced corrosion modeling—A review. *Corros. Sci.* **2019**, *146*, 99–111. [CrossRef]

22. Adumene, S.; Adedigba, S.; Khan, F.; Zendehboudi, S. An integrated dynamic failure assessment model for offshore components under microbiologically influenced corrosion. *Ocean Eng.* **2020**, *218*, 108082. [CrossRef]

23. Behari, N.; Sheriff, M.Z.; Rahman, M.A.; Nounou, M.; Hassan, I.; Nounou, H. Chronic leak detection for single and multiphase flow: A critical review on onshore and offshore subsea and arctic conditions. *J. Nat. Gas Sci. Eng.* **2020**, *81*, 103460. [CrossRef]

24. Taleb-Berrouane, M.; Khan, F.; Hawboldt, K.; Eckert, R.; Skovhus, T.L. Model for microbiologically influenced corrosion potential assessment for the oil and gas industry. *Corros. Eng. Sci. Technol.* **2018**, *53*, 378–392. [CrossRef]

25. Xie, Y.; Zhang, J.; Aldemir, T.; Denning, R. Multi-state Markov modeling of pitting corrosion in stainless steel exposed to chloride-containing environment. *Reliab. Eng. Syst. Saf.* **2018**, *172*, 239–248. [CrossRef]

26. Yazdi, M.; Khan, F.; Abbassi, R. Microbiologically influenced corrosion (MIC) management using Bayesian inference. *Ocean Eng.* **2021**, *226*, 108852. [CrossRef]

27. Adumene, S.; Nwaoha, T.C. Dynamic cost-based integrity assessment of oil and gas pipeline suffering microbial induced stochastic degradation. *J. Nat. Gas Sci. Eng.* **2021**, *96*, 104319. [CrossRef]

28. Fenton, N.; Neil, M. *Risk Assessment and Decision Analysis with Bayesian Networks*, 1st ed.; Taylor & Francis Group: London, UK, 2012.

29. Jensen, F.V.; Nielsen, T.D. *Bayesian Networks and Decision Graphs*, 2nd ed.; Springer: New York, NY, USA, 2007.

30. de Andreis, F. A Theoretical Approach to the Effective Decision-Making Process. *Open J. Appl. Sci.* **2020**, *10*, 287–304. [CrossRef]

31. Robison, L.J.; Shupp, R.S.; Myers, R.J. Expected utility paradoxes. *J. Socio-Econ.* **2010**, *39*, 187–193. [CrossRef]

32. Okoro, C.; Ekun, O.A.; Nwume, M.I.; Lin, J. Molecular analysis of microbial community structures in Nigerian oil production and processing facilities in order to access souring corrosion and methanogenesis. *Corros. Sci.* **2016**, *103*, 242–254. [CrossRef]

33. Srivastava, S.K.; Katarki, M.V.; Cherian, V. Failure analysis of a 30-in subsea oil pipeline. *Mater. Perform.* **2008**, *47*, 52–56.

34. Heredia-Zavoni, E.; Montes-Iturrizaga, R.; Faber, M.H.; Straub, D. Risk assessment for structural design criteria of FPSO systems. Part II: Consequence models and applications to determination of target reliabilities. *Mar. Struct.* **2012**, *28*, 50–66. [CrossRef]

35. Kaiser, M.J. Offshore pipeline construction cost in the U.S. Gulf of Mexico. *Mar. Policy* **2017**, *82*, 147–166. [CrossRef]

36. Richardson, R.; Brugnone, N. *Oil Spill Economics: Estimates of the Economic Damages of an Oil Spill in the Straits of Mackinac in Michigan*; Michigan State University: East Lansing, MI, USA, 2018; Issue May. Available online: https://flowforwater.org/wp-content/uploads/2018/05/FLOW_Report_Line-5_Final-release-1.pdf (accessed on 18 June 2022).