Proceedings of the 2025 Winter Simulation Conference
E. Azar, A. Djanatliev, A. Harper, C. Kogler, V. Ramamohan, A. Anagnostou, and S. J. E. Taylor, eds.

A REVIEW OF KEY RISK MODELING TECHNIQUES FOR OIL AND GAS OFFSHORE DECOMMISSIONING PROJECTS

MD Kashfin[1], Oumaima Larif[1], Suresh Khator[1], and Weihang Zhu[1,2]

[1]Department of Industrial and Systems Engineering, University of Houston, Houston, TX, USA
[2]Department of Engineering Technology, University of Houston, Houston, TX, USA

ABSTRACT

Neglecting the dangers of decommissioning offshore gas and oil facilities can lead to significant environmental destruction, safety risks, legal issues, and other costs that are likely to increase as these outdated structures deteriorate. This paper provides a comprehensive review of risk modeling techniques employed in offshore oil and gas decommissioning projects. Through systematic literature analysis, relevant papers published between 2015 and 2025, the key risk modeling approaches: multi-criteria decision-making frameworks, Bayesian network applications, and sensor/digital-twin/physics-based modeling techniques, were identified. The paper evaluates each type of method's advantages, limitations, and application scope under different decommissioning scenarios. Despite significant advances in risk modeling, persistent gaps exist due to the uncertainty and complexity of the projects. This review serves as a foundation for understanding the current state of risk modeling in offshore decommissioning while identifying critical areas for future research development.

1 INTRODUCTION

The offshore oil and gas industry is essential to the global economy, generating more than $4 trillion in revenue every year while creating close to 40 million jobs. However, with aging offshore infrastructure, more than 7,000 platforms and 35,000 wells globally are reaching the end of their operational life and require responsible decommissioning. Offshore decommissioning involves ceasing production activities and dismantling assets related to them. This encompasses plugging and abandoning (P&A) wells, removing or repurposing subsea and topside structures, detoxifying hazardous substances, and fulfilling safety and environmental requirements. Based on environmental and economic circumstances, options can be full removal, partial dismantling, leave-in-place, partial decommissioning, also known as reefing, or reuse (Watson et al. 2023).

The risk of foregoing decommissioning obligations can lead to catastrophic consequences. Aged structures may collapse, emitting poisonous materials into the sea, which can obliterate ocean life while endangering humanity. Legal noncompliance exposes both operators and governments to significant financial liabilities and reputational risks, which are intensified by increasing regulatory scrutiny. For operators and governments alike, there is no longer an option for sustainable decommissioning - it is a dire responsibility. For instance, the failure to implement sustainable decommissioning practices has led to more than 75% of idle or end-of-life oil wells and platforms in the Gulf of Mexico being overdue for decommissioning as of June 2023. If current policy gaps continue, this backlog could nearly double, surpassing 5,000 wells by 2030. This situation poses an increased risk of pollution and habitat degradation for the environment, while also creating substantial financial liabilities for governments. The total estimated costs for decommissioning all wells and platforms in U.S. federal waters range from $40 billion to $70 billion, with taxpayer-funded cleanups already occurring in instances where operators have defaulted on their responsibilities. (Lockman et al. 2023).

It is essential to evaluate and mitigate all potential hazards at each stage of decommissioning projects carefully in order to achieve sustainability, safety, and compliance with the law. Risk modeling is crucial as it methodically evaluates, investigates, and mitigates potential risks that range from environmental pollution to operational and financial risks. By utilizing risk analysis tools, operators are able to anticipate contingencies, minimize uncertainties, and keep up with more stringent environmental, social, and governance (ESG) and regulatory standards. Aside from protecting the marine environment and human health, it prevents companies from reputational as well as financial losses because of decommissioning failure (Wei and Zhou 2024).

A range of qualitative, quantitative, and hybrid risk modeling techniques exists for various scenarios and risk levels associated with offshore decommissioning. However, no single model provides a universal solution, prompting researchers to continually search for holistic tools suited to the specific decommissioning environment. This situation underscores the complexity and diversity inherent in offshore projects, where multiple factors must be taken into account while developing and selecting a risk model. This paper addresses this gap by providing a comprehensive review of existing key risk modeling techniques through a systematic literature search and analysis. Areas of application, limitations, scopes, and challenges of implementing these risk models are discussed. In addition, current trends and research gaps are also outlined to explore the future research scopes in this area.

2 METHODOLOGY

Systematic literature searching and analysis were conducted to find relevant papers on risk modeling techniques for offshore oil and gas decommissioning projects. The search was performed using a set of predefined keywords, including "offshore decommissioning," "oil," "gas," "petroleum," "risk," "safety assessment," "risk models," and "reliability analysis," among others. Related topics such as offshore nuclear waste decommissioning and wind turbine decommissioning were intentionally excluded to maintain the focus of the review.

Journal articles, conference papers, and review papers published between 2015 and 2025 were sourced from 3 reputable academic databases, Web of Science, ScienceDirect, and Scopus journals. An initial set of 434 papers was identified through these databases using the mentioned keywords. Reference management tool, EndNote21 has been used to carefully categorize, analyze and manage the literatures. After removing duplicate literatures, 3 step questions were asked to ensure that the most relevant literatures were included only. Each paper was screened by asking: firstly, does it address any risks in the context of offshore oil and gas decommissioning projects? Secondly, does it present or investigate a specific mathematical, framework and simulation-based risk modeling technique? And finally, does it consider effects and risks at more than one phase or the whole decommissioning lifecycle?

After removing duplicates and screening the titles and abstracts, 33 papers were relevant where key techniques: multi-criteria decision making (19 papers), Bayesian Network models (8 papers), sensor, GIS, and digital twin-based (6 papers) risk modeling were discussed. In addition to the three primary techniques, there are various other risk modeling approaches, such as artificial intelligence and machine learning methods, probabilistic modeling, risk-based prioritization, asset health assessments, and maintenance models. Nevertheless, due to the volume of published research and citations, the three previously mentioned risk modeling techniques are regarded as fundamental in practice and fall within the scope of this paper. The papers were analyzed to assess how each risk modeling technique was applied as well as the effectiveness and limitations of these models in addressing specific challenges in the field.

The rest of the paper is structured as follows: 1) Section 3 discusses the overview of risks in different stages of offshore oil and gas decommissioning projects, 2) Section 4 provides an overview of the three primary risk modeling techniques. 3) Section 5 presents the existing research gap and future scope. Finally, the paper is concluded with a summary of key findings and implications.

3 RISKS IN DIFFERENT STAGES OF OFFSHORE DECOMMISSIONING

Offshore decommissioning of oil and gas facilities goes through five different main phases: 1) planning, 2) preparation, 3) logistics and transport, 4) onshore treatment, and 5) end-of-life disposal. During the planning stage, project management, engineering appraisal, regulatory compliance review, and risk assessments are conducted to create a sound decommissioning strategy. Risks in this stage include bad risk identification, regulatory non-compliance, and underestimating the complexity of projects, leading to cost escalation or delays. In the preparation phase, the facility and location are cleaned through flushing, plugging, abandoning wells, disposing of and decontaminating equipment, and eliminating hazardous material. The hazards include high unplanned hydrocarbon releases, exposure to hazardous materials, and accidents that can injure workers. Logistics and transport consist of the mobilization of specialized equipment and ships to separate and recover offshore structures, pipes, and cables and transport them onshore. Hazards in this sector encompass accidents at sea, adverse weather conditions, lost cargo, and environmental contamination due to debris or spills. Onshore processing involves the sorting, recycling, or disposal of dismantled items and hazardous waste, with risks associated with improper waste management, environmental contamination, and violations of regulations. End-of-life management entails surveying and decontaminating the site for debris, with the possibility of long-term monitoring or remediation as necessary. Risks in this phase include incomplete clearing, undetected environmental impacts, and regulatory issues. Throughout all five phases, there are continuous hazards in the form of environmental threats due to accidental spills or habitat desecration, occupational health and safety risks to workers, economic risks, and reputational or regulatory consequences due to accidents or noncompliance (ATSE Report, 2024.). Several examples of stage-specific risks are visualized in **Figure 1**.

Risk modeling techniques like quantitative estimation of risk, failure modes and effects analysis, probabilistic modeling, and scenario analysis are required so as to discover, measure, and prioritize such hazards. By applying these methods proactively, organizations can better foresee future issues and implement sufficient controls ahead of problems arising.

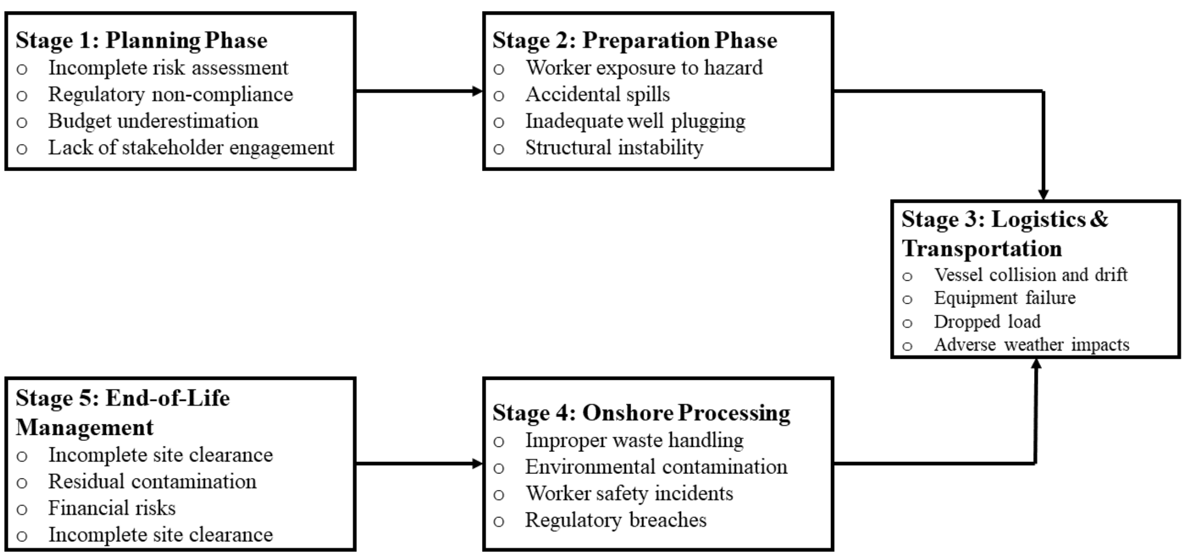

Figure 1. Stages of offshore oil and gas decommissioning projects and examples of associated risks

4 OVERVIEW OF THE KEY RISK MODELING TECHNIQUES

Various qualitative and quantitative risk modeling techniques are utilized to assess risks in the decommissioning process of offshore oil and gas projects, influenced by the complexity, uncertainties, and differing stakeholder opinions. Researchers frequently combine these techniques, drawing from historical data, expert insights, case studies, and regulatory documents. This section discusses the features and application scopes of three major risk modeling approaches: multi-criteria decision making, Bayesian networks, and the use of sensors, digital twins, and GIS-based modeling.

4.1 Multi-Criteria Decision Making (MCDM)

MCDM is a set of methods widely used to make decisions in scenarios with multiple options, often with conflicting criteria. These techniques start with clearly defining the decision criteria, selecting the relevant criteria, and collecting accurate data. Usually, experts are involved in data input and model evaluation.

Previously, financial and cost analysis criteria were considered in the decommissioning decision-making models. However, Al-Ghuribi et al. (2016) integrated net present value analysis for the financial analysis with a weighted scoring technique for non-financial metrics such as environmental, regulatory, and public safety considerations to find the most suitable decommissioning option through a Malaysian offshore context as a case study. Grandi et al. (2017) further emphasized the need for a more robust decision-support system to manage the intricate process of dismantling platforms and mitigating environmental risks. They proposed a framework for planning safe and sustainable decommissioning that incorporates environmental, safety, and logistical considerations, emphasizing a clear definition of the indicators and objective criteria as one of the most critical prerequisites.

Increasing the number of decision criteria makes the model complex and computationally expensive. To solve this problem systematically, many authors suggested using the Analytical Hierarchy Process (AHP), which allows decision makers to break down a complex problem into smaller and more manageable multi-level hierarchies. Na et al. (2017) utilized the Analytical Hierarchy Process (AHP) to rank decommissioning methods for the fixed jacket platform, considering the structural integrity, and it was validated through expert surveys. Similar tools such as Rank Order Centroid (ROC) and Simple Multi-attribute Rating Technique Exploiting Ranks (SMARTER) methods are utilized to find the order of preferences of project teams in selecting decommissioning alternatives for the Alpha Jacket platform in the Brent field in the works of de Lima and Gomes (2021). Khalidov et al. (2023) suggested using the four-level hierarchical structure of the AHP framework while taking account of environmental, social, and corporate governance criteria to get better results for assessing decommissioning options for offshore platforms in California.

Decommissioning subsea pipelines can be hazardous, similar to offshore platforms. Issues like leakage, corrosion, and structural failures may cause environmental damage and economic loss, prompting the researchers to explore pipeline decommissioning risk models. Soares et al. (2023) performed sensitivity analysis based on the decision-making methodology developed by a COPPE/UFRJ research group for the pipelines and umbilical decommissioning (leave in situ and removal options) in Brazil, considering technical sub-criteria: complexity of operations and technological Risk. The results showed the influence of parameters like water depth, structural integrity, and cleaning status in pipeline decommission decision-making. Caprace et al. (2023) selected the PROMETHEE method for multi-criteria decision analysis, designed to rank decommissioning options for pipelines in the context of Brazil. The methodology incorporated 37 attributes grouped into six main criteria: Safety, Environment, Waste Management, Technical, Social, and Economic. The study identified Total Removal of Reverse Reel for umbilical and in situ permanence of flexible water injection pipelines as the most balanced solution. Olatunde et al. (2023) used MCDM to predict the longevity of deep-sea pipelines, incorporating expert judgements and available literature insights in the MCDM to weigh different failure modes, followed by post-MCDM analysis using performance functions and reliability analysis. Their results showed that temperature significantly influences pipeline deterioration.

In recent works, several authors suggested integrating stochastic modeling tools like Markov chains and Monte Carlo simulations with MCDMs to capture the random nature and uncertainties inherent in decommissioning decisions. Moraes et al. (2022) introduce a Markov Chain approach to MCDA for modeling dynamic decision-making processes by defining transition rates based on the performance of alternatives as well as handling uncertainties without relying on user-defined parameters. They validated the model through a case study of the Brent field. de Lima et al. (2023) proposed a multi-criteria decision-making methodology: SMAA-ExpTODIM, which is a combination of Stochastic Multicriteria Acceptability Analysis (SMAA) with Multi-criteria Interactive Decision Making in its exponential formulation, and they applied it to Marlim and Voador production fields' flexible line to evaluate decommissioning options. Their model incorporates various decision makers' perspectives to address uncertainties and ignorance in decision making by adding Monte Carlo simulations and exponential formulation of the decision variables. Similarly, Tavora et al. (2024) utilized Monte Carlo simulations in the MCDA models to handle uncertainties in evaluating the available decommissioning options for subsea pipelines in Brazil. Their results highlighted leaving the pipelines in place as the preferred strategy over completely removing them.

Often, High-Impact Low-Probability (HILP) events are not considered in the traditional risk modeling techniques. Li and Hu (2022) used impact energy thresholds and spatial overlaps to develop a Domino Effect Risk Assessment System that incorporates two event layers—primary and domino events. They used their model to find whether the consequences of one event can trigger other failure events for the case of Well P&A, platform preparation, and pipeline decommissioning in a recursive manner. They enhanced this model as the Hierarchical Analyst Domino Evaluation System (HADES) model by integrating AHP, which uses structured causality matrices and severity criteria databases. HADES can be utilized to address procedural risks throughout the decommissioning project lifecycle by classifying hazards, assessing primary accidents, and tracking escalation scenarios (Li and Hu 2023a). This work was further enhanced by developing a modular, quantitative system called MADM-Q, which integrates three sub-models—Engineering Cost Evaluation System (ECES), Hierarchical Analyst Domino Evaluation System (HADES), and Composite Impact Evaluation System (CIES)—to evaluate decommissioning cost, risk (notably from Domino Effect Accidents), and environmental-socioeconomic impacts (Li and Hu 2023b).These models aid in the critical investigation of risk assessments by identifying worst-case scenarios for hazardous incidents of the decommissioning projects.

Decommissioning oil and gas offshore structures involves significant environmental risks. Several authors have developed specialized decision-making frameworks based on comparative assessments to evaluate the environmental impacts of these structures. Thomas et al. (2021) proposed an integrated framework incorporating risk mapping, cost-benefit analysis, and scenario evaluation, with particular attention to cumulative effects in the environment and regional biodiversity in contexts of Australia's regulatory planning. The framework was developed through extensive stakeholder engagement and validated against existing infrastructure datasets. Nicolette et al. (2023) introduced a Net Environmental Benefit Analysis-based Comparative Assessment (NEBA-CA) framework to address the multigenerational environmental impacts for the case of the North Sea Jacket platform. Carneiro et al. (2024) introduced a methodology to assess the environmental impacts of decommissioning subsea installations in Brazil by assigning quantitative scores to environmental pressures derived from specific decommissioning activities and combining these with ecological sensitivity scores based on threatened species and critical habitat presence. The framework was used to identify high-risk zones and flagged infrastructure.

Some systematic frameworks are used in MCDM for offshore decommissioning. Through literature review, Vidal et al. (2022) developed a systematic risk-based decision support framework for the case of the North Sea that identified the interconnection between the stakeholder preferences, technological feasibility, and impact assessments to develop a decommissioning strategy. Similarly, Jalili et al. (2024) proposed a bottom-up problem formulation for multi-criteria decision analysis (MCDA) for pipeline decommissioning in the North Sea. These systematic frameworks account for factors such as site-specific data, operational parameters, safety, costs, energy usage, and environmental risks.

Besides the mentioned works, Miraj et al. (2024) studied the impact of Knowledge Management (KM) and Database Management Systems (DBMS) on decision-making in subsea project services. Also, Systematic review papers by Y. Li et al. (2022) and Wei et al. (2024) on investigating the main factors associated with multi-criteria decision-making (MCDM) for decommissioning can serve as a foundational resource for accelerating research in this sector.

4.2 Bayesian Networks (BNs)

Bayesian Networks (BNs) have been popularly used in risk modeling of decommissioning projects due to their capability to represent complex conditional dependencies among interrelated risk factors under uncertainty and the feature of combining with other qualitative and quantitative techniques, offering robustness of the model. Several types of BNs are used in the crucial stages, such as plugging and abandonment (P&A), pipeline decommissioning, and heavy-lift operations, where decision-making must consider numerous interacting variables over time.

Traditional probabilistic risk analysis approaches, such as fault trees, event trees, and bow tie analysis, have limited capabilities in handling evolving plug and abandoned wells conditions due to uncertain scenarios and data unavailability. Arild et al. (2019) used a Bayesian reliability approach to estimate the time-to-failure of barrier systems in the permanently plugged and abandoned wells. Survival data, expert input, and physicochemical degradation models were used to model the risks despite having a scarce dataset in the context of the North Sea region. This work was enhanced by Babaleye et al. (2019) who developed a BN structure utilizing advanced logics such as Noisy-OR and leaky Noisy-OR. In their two additional studies, they integrated Hierarchical Bayesian Modeling (HBM) with Bayesian Networks (BN) (Babaleye et al. 2019a) and included both analog data and expert judgment. This methodological approach improved the BN's capacity to model risks, particularly in identifying hazards related to abandoned wells, ensuring personnel safety, and mitigating asset loss during the removal of heavy offshore structures (Babaleye et al. 2020)

Fam et al. (2020) enhanced this work by integrating a Dynamic Bayesian Belief Network (DBN) that accounted for failures and human errors through performance-shaping factors. They analyzed variable dependencies using historical datasets and expert opinions. This analysis aimed to identify significant relationships between human errors, incident causation, and accident severity.

Li et al. (2022) introduced a model based on the Copula-Bayesian technique to evaluate the risk of decommissioning aging subsea pipelines. Their framework captured nonlinear and multivariate dependencies among 23 operational and environmental risk variables. This model also aids in a comprehensive understanding of complex risk drivers in pipeline decommissioning, such as improper cutting, operational errors, and unqualified construction practices. They conducted another study assessing the economic life to optimize maintenance and decommissioning decisions of subsea pipelines by incorporating influence diagrams within a Bayesian network framework for a comprehensive cost-benefit analysis of various offshore pipeline decommissioning options (Li et al. 2024). Han et al. (2024) extended this study by developing a dynamic Continuous Bayesian Network (CBN) model, where corrosion and fatigue dependencies in pipelines were considered to perform reliability and economic assessment.

4.3 GIS, Sensors, and Digital-Twin-based Models

Traditional risk models frequently face challenges in predicting the dynamic risks linked to offshore decommissioning projects due to their dependence on static data. By incorporating advanced real-time monitoring technologies, such as digital twins, sensor data, and Geographic Information Systems (GIS), into these risk models, it becomes possible to enhance dynamic risk assessment, evaluate structural asset integrity, and model environmental risks associated with decommissioning initiatives.

Utilizing high-resolution spatial data on commercial fishing activity from the vessel monitoring systems in the North Sea, Rouse et al. (2017) proposed a GIS-based model to perform comparative assessments of decommissioning options of the pipeline, considering fishing intensity near the pipeline area as a factor, that can be utilized in evaluating safety and economic risks associated with leaving pipelines in situ. Similarly, Liu et al. (2018) used a time-series approach (TSRS) from 26,000 satellite images across the Gulf of Mexico to assess the condition of offshore platforms to make decisions on decommissioning. Their proposed method accurately identified platform existence and status through optimized geo-correction and temporal persistence analysis. Böttner et al. (2020) developed a risk assessment framework for plugged and abandoned wells in the North Sea using a combination of 3D seismic data and hydroacoustic water column imaging. Their methodology identified active gas release in 28 of 43 investigated wells, and they discovered the correlation between leakage risks and shallow gas accumulation near the wellbores.

Given the inherent complexity and uncertainty of decommissioning projects, the application of digital twins aids in risk modeling through simulation-based analysis. Neves et al. (2023) proposed a digital twin framework, structured from inspection data, sensor inputs, and material deterioration models to estimate the failure probabilities of floating production, storage, and offloading (FPSO) units. Their proposed model combines finite element model updating (FEMU), corrosion degradation models, and structural reliability analysis to predict failure probabilities.

Oil and gas assets deteriorate due to physical mechanisms such as fatigue and corrosion. Incorporating these physical failure phenomena in risk modeling helps to understand the impact of surrounding physical activities. (Joavina et al. 2017) combined probabilistic spectral analysis with fatigue assessment techniques to analyze progressive fatigue damage in the self-lifting Romanian offshore platform "Gloria". The model quantified annual yield probability as a function of sea state and used Kellogg stress concentration factors with S-N curves and Palmgren-Miner rule to evaluate cumulative fatigue damage. The results indicated that low and moderate sea states contribute to long-term degradation in the offshore structure. Using nonlinear pushover analysis and time-dependent corrosion models, (Kim et al. 2017) investigated the structural performance of a corroded jacket platform in Malaysian waters. They found that under average corrosion conditions, the platform remained safe for operation for up to 50 years, whereas under severe corrosion, its structural integrity failed beyond 35 years.

5 RESEARCH GAPS AND FUTURE RESEARCH SCOPES

Despite advances in risk modeling techniques for offshore oil and gas decommissioning projects, significant research gaps persist that hinder comprehensive risk assessment across the entire decommissioning lifecycle. Current methodologies such as MCDM, Bayesian Networks, and physics-based modeling typically address isolated phases rather than providing an integrated framework that spans from planning to end-of-life management. Data scarcity remains a fundamental challenge, with many models relying heavily on expert judgment rather than empirical data, introducing inherent subjectivity and uncertainty into risk assessments. Scaling these risk models to consider a large number of factors and criteria requires complex models and makes the task computationally expensive. There is limited research on integrating advanced technologies such as AI, digital twins, and real-time sensor data into risk models.

Future research should aim to create comprehensive risk modeling frameworks that dynamically incorporate real-time data alongside modern technologies. Additionally, research should focus on better integration of all types of stakeholder perspectives into decommissioning decisions. Future work should bridge engineering, environmental science, economics, social science, and decision theory to develop more holistic approaches to decommissioning challenges. Besides, there is also a need for adaptive and robust, yet computationally efficient models.

The complexity of decommissioning decisions requires inter-disciplinary research approaches. Systems engineering-based life cycle assessment models have the capability to play a pivotal part in addressing this challenge (Fet et al. 2013). This approach offers a holistic approach to evaluate the energy, environmental, and economic sustainability of such complex systems, moving beyond independent phase evaluation to integrated risk models across the lifecycle. However, more dedicated research is largely necessary for the full evolution and implementation of systems engineering and life cycle assessment-based risk models for the oil and gas offshore decommissioning projects.

6 CONCLUSION

This review demonstrates the considerable evolution of risk modeling in offshore oil and gas decommissioning from simplistic, cost-driven models to holistic frameworks incorporating environmental, safety, regulatory, technical, and socioeconomic considerations. While earlier models primarily addressed financial commitments, recent advancements utilize multi-criteria decision-making (MCDM), Bayesian networks, GIS, sensor integration, and digital twins to more effectively tackle the complex and interrelated risks involved in decommissioning activities. Despite these advances, the majority of current methods still lack coverage of the dynamic, uncertain, and interdependent nature of risks from planning through the end-of-life management phase. As the global offshore decommissioning market continues to expand through 2025 and beyond, the need for sophisticated, integrated risk assessment frameworks becomes increasingly critical. Future risk models should utilize the systems engineering and life cycle assessment frameworks to allow the development of more adaptive, cross-disciplinary risk models that are robust, transparent, and can integrate real-time data and stakeholder inputs throughout the whole decommissioning process. By addressing the identified research gaps and advancing risk modeling capabilities, the industry can move toward safer, more cost-effective, and environmentally responsible decommissioning practices, ultimately enhancing the sustainable management of aging offshore infrastructure across global waters.

ACKNOWLEDGMENTS

The paper is partially sponsored by a U.S. Department of Education grant P116S230007 "Developing Modeling and Simulation based Programs at the University of Houston."

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AUTHOR BIOGRAPHIES

MD KASHFIN is a current Ph.D. student in the Industrial Engineering department at the University of Houston. His research interests include in system simulation and decision modeling for complex systems. His email address is mkashfin@cougarnet.uh.edu

OUMAIMA LARIF received her Ph.D. in Industrial and Systems Engineering from Mississippi State University, where she also earned a Master of Science in Aerospace Engineering and a master's degree in industrial engineering. She holds a bachelor's degree in aerospace engineering from the International University of Rabat. Currently, she serves as a Postdoctoral Fellow at the University of Houston. Her research expertise includes systems simulation, virtual reality, and performance measurement. Her email address is olarif@cougarnet.uh.edu

SURESH KHATOR is a Professor of Industrial Engineering and the Senior Associate Dean for Graduate Programs and Computing Facilities at the University of Houston. He earned his Ph.D. in Industrial Engineering from Purdue University. Dr. Khator has held various academic and administrative positions, including at the University of South Florida and the Chinese University of Hong Kong. His research focuses on manufacturing and production systems, and he is a Fellow of the Institute of Industrial and Systems Engineers. His email address is skhator@Central.uh.edu, and his website is https://www.ie.uh.edu/faculty/khator

WEIHANG ZHU is a Professor and Program Coordinator for the Mechanical Engineering Technology program in the Department of Engineering Technology, with a joint appointment in the Departments of Mechanical Engineering, Industrial Engineering, Electrical and Computer Engineering, Cullen College of Engineering, University of Houston, Houston, Texas. His research expertise areas include engineering education, design and manufacturing, automation and robotics, machine learning/deep learning, computational optimization, and mariner and offshore safety. His email address is wzhu21@Central.uh.edu, and his website is https://coss.egr.uh.edu/