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RESEARCH ARTICLE

Implementation of a Combined Fuzzy Controller Model to Enhance Risk Assessment in Oil and Gas Construction Projects

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ABSTRACT The aim of this research is to enhance Oil and Gas (O&G) construction risk assessment using Fuzzy-based Failure Model Effect Analysis (FMEA) through the lens of O&G project managers in the U.S. A mixed-method approach was adopted for data collection, analysis, and processing, including semi-structured interviews with project managers to identify the key risks facing O&G construction projects; a Fuzzy-based FMEA to quantitatively analyse the level of significance of O&G risks; surveys to rank the assessment dimensions of the developed model and their components; and open-ended surveys to validate and verify the assessment model and its outputs, further expanding on the root causes of significant risks based on the assessment outputs, and to propose mitigation strategies for these risks. The research identified 41 risk factors classified under six categories, namely: management, technical and quality, financial and economic, health, safety, environmental, legal, and stakeholders' risks. In addition, the risk assessment revealed that non-compliance with PPE regulations emerged as the most significant risk factor across all categories of O&G risks. This study offers valuable insights by assisting practitioners in better understanding the significant O&G risks that need to be addressed to ensure the successful execution and completion of O&G projects.

INDEX TERMS Oil and gas, control system, fuzzy set theory, decision process, construction industry, risk assessment, project managers, FMEA.

I. INTRODUCTION

The oil and gas (O&G) industry in the U.S., a sector of strategic importance, plays a critical role in shaping the country's economic and energy landscape. This industry not only significantly contributes to the national economy but also is pivotal in the U.S.'s pursuit of energy self-sufficiency [1], [2]. It leverages vast reserves and complex technologies for the extraction and processing of natural resources [3], underscoring its role in reinforcing the nation's journey towards energy independence. Beyond its primary role in energy production, the industry exerts a substantial influence across various sectors, notably in petrochemicals, transportation, and pharmaceuticals, underlining its broad industrial impact [4]. Additionally, its considerable contributions to public infrastructure and essential services highlight its socio-economic significance [5]. Despite the global trend towards renewable energy, the O&G sector remains

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a fundamental component of the U.S. energy landscape, as indicated by the Energy Information Administration (EIA) in 2022. This reliance underscores the necessity for increased production capacity, and thus the need for expanded and efficient O&G infrastructure. This, however, brings forth a set of complex risks associated with the construction of O&G projects. These projects are distinguished by their unique characteristics: advanced technological demands, remote locations, and the involvement of a diverse array of stakeholders [6], [7] [8]. These factors contribute to the complexity of such projects, necessitating strict adherence to schedules, budgets, and quality standards to ensure their successful completion and delivery [9]. This complexity is not just a logistical-related but also reflects the evolving nature of the energy sector, where balancing growth, efficiency, and environmental concerns becomes increasingly pivotal. A prominent risk in this context is related to the dynamic regulatory and political landscape [10]. Shifts in government policies, permitting processes, and environmental regulations introduce a new set of risks, resulting in potential delays, impacting project timelines and costs. Economic factors, particularly the volatility in O&G prices and market demands, also present critical financial risks to these projects, affecting their overall performance and viability [11]. Another layer of risks is added by the requirement for cutting-edge technology and specialized labour. The reliance on specific expertise and sophisticated equipment, coupled with the current shortage of skilled professionals, leads to operational difficulties, delays, and inflated costs [10], [12]. Furthermore, these projects are vulnerable to natural disasters, such as hurricanes, which pose significant risks to construction operations and worker safety. Given the multitude of risks in O&G projects, stakeholders in U.S. O&G construction projects face substantial pressure to ensure operational safety, meet regulatory compliance, maintain environmental sustainability, and achieve high performance in construction operations, while also adhering to the agreed budget, duration, and quality standards. This highlights the critical importance of risk management in project management activities, particularly emphasizing the risk assessment phase as a key component. Risk assessment involves the systematic identification and analysis of potential risks. Risk assessment is the process that involves identifying and analysing potential risks and quantifying their significance either qualitatively or quantitatively. The effective application of risk assessment for prioritizing potential risks based on their multi-dimensional impacts can effectively help in the development of robust response strategies [13], tailored to mitigate these risks, thereby ensuring that projects are completed within the designated timeline and budget, while adhering to safety, environmental, and quality standards [14].

The motivation behind conducting this research stems from a notable gap in existing studies concerning the complex relationship between risks and the success of O&G projects. While some research efforts have been made, as evidenced by studies from [8], [15], [16], and [17], there remains a significant deficiency in the literature regarding the quantitative analysis of the various dimensions of risks impacting the implementation and delivery of O&G construction projects. This gap is particularly evident on both a global scale and within the specific context of the U.S. construction industry. To this end, this study aims to fill this gap by identifying and quantitatively assessing the significance of key risks inherent in O&G projects within the U.S. under fuzzy environment that can significantly enhance the ability to capture the multi-dimensional effects of risks across different categories such as technical, financial, legal, and managerial aspects. These insights are crucial for understanding how risks can potentially affect project success metrics, including cost management, adherence to schedules, and adherence to quality standards. Furthermore, by focusing specifically on the U.S. context, this research aims to explore the unique challenges and opportunities present within the country's O&G industry. This includes considerations such as regulatory frameworks, market dynamics, and technological advancements that may influence risk profiles and project outcomes, enabling stakeholders to gain a comprehensive understanding of these factors and develop more informed risk management strategies tailored to the specific needs of O&G construction projects in the U.S. Ultimately, the goal of this research is not only to advance academic scholarship in the field but also to provide practical insights that can directly benefit industry practitioners, contributing to the sustainable growth and resilience of the O&G industry in the U.S.

The research contributions can be summarized as follows:

1. We identified and classified the key risks facing the successful implementation and delivery of O&G construction projects in the U.S., shedding light on the complex risk landscape specific to this sector. The identification of key risks in O&G construction, obtained through the perspective of construction project managers, provides invaluable guidance for industry decision-makers, enabling them to navigate and mitigate risks effectively. Furthermore, the findings contribute significantly to the academic discourse on risk assessment in the oil and gas industry, enriching the understanding of the key risks inherent in O&G construction projects [18], [19].

2. We developed a novel model for analysing the level of significance of O&G risks using a Fuzzy-based FMEA. By considering the key components of each analysis dimension—organizational readiness and external factors for risk probability; impact on cost, schedule, quality, and health and safety for risk impact; and technological advancements, frequency of risk monitoring, and cross-functional team collaboration for risk detection—the model's accuracy in predicting O&G risk levels has significantly improved. Furthermore, the quantification of risks using the developed risk assessment model aids in the development of a risk-aware culture within organizations, where decisions are based on data-driven insights rather than intuition [56], [57]. This shift towards a more analytical and evidence-based approach in managing risks can significantly enhance the overall

safety, quality, and reliability of O&G construction projects. Allocating a FRN to each risk factor provides a quantifiable method to assess the risk level of the identified O&G risks, thus guiding practitioners in prioritizing and strategizing their mitigation efforts [20], [21]. This is particularly necessary in the context of O&G construction projects, where the dynamic environment and involvement of numerous stakeholders introduce various risks and uncertainties [22], and thus makes it invaluable for efficient resource allocation and informed decision-making [60]. For example, the high risk associated with PPE lack of compliance necessitates allocating substantial resources towards effective safety training, regular compliance checks, and perhaps investing in better quality PPE. In cases like poor project communication, the emphasis might shift to investing more in advanced communication technologies to foster clarity and consistency in information sharing.

3. We identified the primary root causes and key mitigation strategies corresponding to significant O&G risks, based on the analysis outcomes from the developed Fuzzy-based FMEA risk assessment model. This can provide industry practitioners and researchers with critical insights to develop a comprehensive best practices framework that not only effectively addresses and mitigates risks within the O&G industry but also enhances resilience and operational reliability through the continuous and sustainable management of risks.

The remainder of the manuscript is organized as follows: In Section I, the introduction is presented. In Section II, the need for an enhanced risk assessment model for complex systems is justified. In Section III, previous work is reviewed. In Section IV, the aim and associated objectives are outlined. In Section V, the research methodology is detailed. In Section VI, the results and analysis are presented. In Section VII, the key findings of this research are discussed. Finally, Section VIII presents the conclusions of the work.

II. THE NEEDS FOR AN ENHANCED RISK ASSESSMENT METHOD FOR COMPLEX CONSTRUCTION PROJECTS

In the complex and evolving landscape of O&G construction projects, the implementation of risk assessment is of high significance for ensuring the safety, efficiency, and cost-effectiveness of construction operations and workforce. Yet, most of the current methods for risk assessment bear notable constraints that hinder their efficacy within this industry. For instance, multi-criteria risk analysis methods like risk matrices and failure mode and effects analysis (FMEA). These methods, while user-friendly and intuitive, suffer from subjectivity in assessment and an oversimplification of complex risks [23], [24]. In fact, the subjective nature of these methods can lead to inconsistencies and biases in risk assessment, as judgments about probability and impact are often based on personal or collective expert opinions [25], [26]. Furthermore, they tend to reduce the multi-dimensional effects of risks to a singular effect, potentially overlooking the complex and interconnected nature of risks in large-scale and complex construction projects, such as those in the O&G industry, leading to an oversimplified view of the risk landscape. Similarly, the Analytic Hierarchy Process (AHP) offers a structured decision-making framework but struggles with scalability in large projects due to the complexity of pairwise comparisons [27]. Its reliance on expert judgment introduces subjectivity and potential biases, as discussed by [28], and it faces challenges in maintaining consistency in judgments and handling the uncertainties commonly encountered in complex projects. Decision trees are another method used in risk assessment, but like the others, they have their own set of limitations, particularly when applied to complex construction projects like O&G projects. Their tendency to oversimplify complex scenarios, reliance on extensive data, and binary nature can be inadequate for the complex risks in these projects [22], [29]. Moreover, the static format of decision trees struggles in the dynamic construction environment, where risks and conditions rapidly change. AI-based methods for risk assessment, despite their proven benefits, are hindered by their dependency on extensive historical data for training [30], which is often not available or insufficient in the O&G construction context. Additionally, these models involve complex programming and coding, necessitating specialized skills, which can be a resource-intensive barrier [31]. Furthermore, adaptability issues arise, as these models may not efficiently adjust to new or evolving risks—a critical drawback in the dynamic environment of O&G projects where risk factors can change rapidly. Finally, Bayesian networks, known for handling uncertainties and capturing risk dependencies [32], depend heavily on accurately formulated causal relationships and necessitate extensive, specific data [33], [34], as well as a high level of statistical and domain-specific knowledge, which can be difficult to obtain for such complex systems. To this end, there is a need to develop a risk assessment model that (1) reduces the subjectivity and biases inherent in expert-based methods, (2) addresses the oversimplification of complex risks by considering the multidimensional effects on project outcomes, and (3) is less reliant on complicated mathematical, statistical, or coding techniques that may discourage decision-makers from engaging thoroughly with quantitative risk assessment.

III. RELATED WORK

As indicated in Table 1, prior work considering risks in O&G construction projects has mainly focused on qualitatively assessing the impact of the risks facing these projects, often using risk matrices, as in the work of [35] and [36]. These studies used probability and impact matrices to analyze the level of significance of the identified risks based on a systematic literature review. However, they neglected direct stakeholder-specific insights, such as those from project managers, for risk identification and failed to analyze the identified risks in a reduced-ambiguity and bias risk quantification environment, like fuzzy set theory. This

TABLE 1. Prior work and knowledge gap identification.

Reference	Region	Purpose	Data collection, analysis, and processing method(s)	Results
[8]	Malaysia	Evaluated the influence of external risk factors such as political, economic, social, environmental risks, and government support on the successful delivery of O&G projects in Malaysia.	Questionnaire surveys and Structural Equation Modelling	Results showed that each external risk factor (political, economic, social, and environmental), coupled with government support, had a significant positive effect on the success of projects. However, the moderating role of government support on the impact of these risk factors was not substantial.
[16]	Yemen	Explored the correlations between external risk factors and their effects on the successful completion of O&G construction projects	Questionnaire surveys, and Partial Least Square Structural Equation Modelling.	Results showed that economic, political, force majeure, and security-related risk factors were among the significant risks impacting the success of O&G construction projects.
[35]	Yemen	Identified and analysed the major risks associated with construction projects within Yemen's O&G industry.	Systematic literature review, questionnaire surveys, and a probability-impact matrix.	Results indicated that delays in decision making, lack of contractors' experience, insufficient consultant's experience, improper project feasibility study, inadequate tendering, shortages and low productivity of labour, inappropriate organizational structure, and political instability were among the significant risk factors identified in this study.
[36]	Iraq	Identified and analysed risks caused by Third Party Disruption in the construction of O&G pipelines, aiming to develop a holistic Risk Management Model.	Systematic literature review, semi-structured interviews, questionnaire surveys, and a probability-impact matrix.	Results revealed that sabotage, and theft are critical safety risks, while official corruption and lawlessness were identified as significant risks confronting pipeline construction projects.
[37]	Iran	Evaluated the risks associated with the construction projects of the South Pars gas field, with an emphasis on schedule delays and cost overruns.	Interviews and Bayesian networks	Results indicated that shortages of resources, unforeseen activities, and contractor financial difficulties were identified as significant risks adversely impacting O&G construction projects.
[38]	Yemen	Investigated the relationships between internal risks and their adverse impact on the success of O&G construction projects	Questionnaire surveys, and Partial Least Square Structural Equation Modelling.	Finding revealed that factors related to project management, feasibility study-design, and the supply of resources and materials were the most critical internal risk factors impacting the success of O&G construction projects. Additionally, the research underscored the significance of these elements in formulating strategies for risk response.

oversight likely compromised the efficacy and accuracy of the risk quantification process. Additionally, specific risk categories were the focus of other studies, such as that by [37], which concentrated on schedule and cost risks, neglecting other risk types like safety, technical, legal, or management-related risks. Other research efforts, including those of [8], [16], and [38], aimed to capture the total effects of risk categories on project success using structural equation modelling. Although they succeeded in this endeavour, they did not address the quantified effects of each risk factor within each category. Furthermore, most of the prior work studied the impact of these risks in developing countries, which limits the applicability and generalisation of their findings to developed countries like the U.S., given the unique challenges facing developing countries are different from those facing developed countries, as indicated in the works of [39] and [40]. To this end, prior work falls short in several key areas: (1) identifying and classifying a comprehensive list of O&G construction risks from the perspective of specific stakeholder groups; (2) capturing these risks in O&G construction projects executed in developed countries, and (3) quantitatively assessing the level of impact of these risks on the successful execution and completion of O&G projects.

IV. AIMS AND OBJECTIVES

The aim of this research is to enhance O&G construction risk assessment using Fuzzy-based FMEA from the perspectives of O&G project managers in the U.S. The research objectives are to (1) identify and categorize the significant risks that impact the successful execution and completion of O&G construction projects in the U.S.; and (2) conduct a quantitative assessment to determine the importance of these identified risks in O&G projects.

V. RESEARCH METHODOLOGY

In this study, we implemented a two-step mixed-methods approach for data collection, analysis and process. Details on each of the adopted steps are provided in the following subsections:

A. STEP ONE: IDENTIFICATION OF O&G RISKS

In this step, the authors conducting semi-structured interviews with nine project managers working in O&G construction projects in the U.S., following the ethical approval from Trinity College Dublin. The objectives of the interviews were to (1) identify and classify the key risks facing O&G construction projects in the U.S.; (2) assess the suitability of using FMEA for analyzing O&G construction risks and explore the possibility of tailoring the existing FMEA model for these projects; and (3) establish conditional statements between the components of the assessment dimensions of FMEA to construct a fuzzy inference system for risk assessment. This method of data collection was selected for its ability to provide in-depth insights and the flexibility to explore diverse viewpoints [19]. All participants had over 10 years of construction project management experience and were active members of professional bodies such as the American Society of Civil Engineers, the American Society for Engineering Management, or both.

B. STEP TWO: DEVELOPMENT OF FUZZY-BASED FMEA MODEL FOR O&G RISKS

FMEA is a qualitative risk analysis method that evaluates the significance of potential risks by considering three key parameters: the likelihood of their occurrence, their impact on project objectives, and the capability to detect risks prior to their actual occurrence [41]. This method is widely used by scholars for risk assessment in various engineering and construction disciplines [42], [43]. Based on the outcomes of semi-structured interviews, the FMEA model was further expanded by adding new components to each risk analysis dimension. Ultimately, the Risk Probability of occurrence (RP) was measured based on organizational readiness (or) which includes the availability of resources, technical expertise, contractual, legal, and financial expertise, training and development programs, and stakeholder engagement and communication, and external factors (ef), encompassing market dynamics, regulatory compliance, socio-economic conditions, and environmental influences. The Risk Impact (RI) was measured based on four components, namely: Impact on Cost (ic), impact on schedule (is), impact of quality (iq), and impact of health & safety (ihs). Finally, the Risk Detection (RD), was measured depending on the following three components: technological advancements (ta), frequency of risk monitoring (frm), and cross-function team collaboration (ctc). Despite the increased efficacy of FMEA achieved by incorporating new components into each analysis dimension, the risk analysis process remains subjective and heavily reliant on expert input. This input, derived from their past project experience, insights, and intuitions, plays a significant role in managing project risks. However, there is considerable uncertainty and bias regarding the efficiency and efficacy of decisions when analyzing and ranking risks qualitatively [32], [44]. This uncertainty stems from the subjective nature of qualitative analysis, which is influenced by personal judgments, experiences, preferences, and cognitive biases, all of which can significantly affect the efficacy of the risk assessment process [45], [45]. Consequently, the proposed model was employed in a fuzzy environment to control inconsistencies and biases in risk analysis. The significance of Fuzzy Set Theory (FST) is highlighted in situations where decision-makers face uncertain, ambiguous, or vague data. Originating from Zadeh's 1965 work, Fuzzy Set Theory (FST) offers a mathematical method for handling data that is too complex, imprecise, or poorly defined for processing by conventional algorithms [37]. Parallel advancements in neural networks also address similar challenges of complexity and imprecision in data, though through distinct computational frameworks that emphasize learning from large datasets and pattern recognition [46], [47]. Risk-based fuzzy models are highly effective in managing the inherent uncertainty and ambiguity in O&G construction projects, which are often influenced by fluctuating market prices, geopolitical factors, and environmental considerations. These models excel by allowing the expression of imprecision, typical in human judgment, through the quantification of terms like "high risk" or "probable delay" into fuzzy sets that represent a range of possibilities rather than a binary outcome [48]. Furthermore, the integration of fuzzy logic enhances decision-making, as it utilizes linguistic variables that reflect natural human communication about [49]. This enables project managers to assess risks with greater granularity—from "very high" to "very low"—each associated with a specific fuzzy set, leading to improved accuracy and effectiveness in risk assessment. Additionally, these models provide flexibility since they do not demand precise input data and can work effectively with estimates, facilitating continuous risk evaluation throughout a project's lifecycle [50]. They also improve the communication of risk to stakeholders by presenting risk in terms intuitive to non-experts, thereby enhancing stakeholder engagement in managing risks. However, employing fuzzy models comes with challenges, including the complexity of model design and the need for deep understanding of fuzzy logic to interpret fuzzy outputs accurately [51]. The subjectivity in setting membership functions can introduce biases and inconsistencies, particularly as different experts may have varying opinions on these settings [52]. Integrating fuzzy models into existing risk management frameworks can also be problematic, as these are often designed for deterministic inputs and may need significant adjustments to handle fuzzy inputs. Moreover, the computational demands of fuzzy models, particularly in complex scenarios, can be substantial, requiring advanced software and computational resources [53]. For example, in assessing the risk of project delays due to regulatory approvals in an OG project, fuzzy models allow risk assessors to define linguistic variables like "unlikely," "possible," and "likely" for delay likelihoods, and "minor," "moderate," and "severe" for potential impacts, with each category backed by a detailed membership function. These inputs help in creating a risk profile that aids decision-making by providing a nuanced view of potential delays, enabling project teams to prioritize actions based on a continuum of risk levels instead of a simple high/low risk assessment. Setting up such models necessitates expert knowledge in fuzzy logic and a thorough understanding of the project specifics to define appropriate membership functions and effectively interpret the model outputs. The key advantage of fuzzy sets, compared to classical set theory, lies in their ability to capture the vagueness of concepts due to uncertainty and human subjectivity. The philosophy of fuzzy logic was established by introducing the degree of membership of a linguistic variable as an alternative to the binary membership of 0 or 1. In fuzzy sets, the transition for an element from non-membership to membership is gradual rather than abrupt, unlike in crisp or classical sets, where the transition is abrupt. This transition among different degrees of membership aligns with the idea that the boundaries of fuzzy sets are vague and ambiguous. Figure 1 shows the structure of the FMEA process based on FST for analyzing the O&G risks. MATLAB (Version R2023a) was used to develop the assessment model, which comprises four fuzzy controllers. To this end, the authors utilized MATLAB (Version R2023a) to develop the assessment model, which comprises four fuzzy controllers. Fuzzy Controller 1 calculates RP based on two analysis components: or and ef. Fuzzy Controller 2 calculates RI based on four components: ic, is, iq, and ihs. Fuzzy Controller 3 calculates RD based on three components: ta, frm, and ctc. Lastly, Fuzzy Controller 4 calculates the RPN for each O&G construction risk factor, using the main risk assessment dimensions, namely RP, RI, and RD. In each controller, the dimensions of risk assessment and their components were fuzzified using trapezoidal membership functions. A trapezoidal membership function is defined by a quadruple of parameters (a, b, c, d), which demarcate the boundaries and the core of the fuzzy set, thereby establishing a trapezoidal shape. Specifically, these parameters represent the following:

- a and d correspond to the lower and upper bounds, respectively, beyond which the degree of membership of any element to the fuzzy set is considered zero.
- b and c delineate the "core" or "plateau" region where elements possess full membership (i.e., a membership degree of 1) within the fuzzy set. The formal mathematical representation of the trapezoidal membership function, μA(x), for an element x in relation to a fuzzy set A, is articulated through a piecewise function as follows:

$$\mu_A(x) = \begin{cases} 0 & \text{for x} \le \text{a}, \\ \dfrac{x-a}{\text{b}-\text{a}} & \text{for a} < \text{x} \le \text{b} \\ 1 & \text{for b} < \text{x} < \text{c}, \\ \dfrac{\text{d}-\text{x}}{\text{d}-\text{c}} & \text{for b} \le \text{x} \le \text{d}, \\ 0 & \text{for x} \ge \text{d}. \end{cases} \quad (1)$$

This type of membership functions was chosen over other types of functions due to their flexibility in representing uncertainty, computational simplicity, interpretability, and ability to handle overlapping ranges effectively, striking a good balance between granularity and system complexity [54]. Following this procedure, the fuzzy inputs were evaluated systematically using Mamdani's fuzzy inference system. This was to determine the calculative level associated with each assessment dimension and, subsequently, the aggregate level of riskiness of each O&G risk factor. This process was achieved by employing a defined set of IF-THEN conditional statements. The outcomes were then defuzzified to calculate a Fuzzy Risk Number (FRN) using the centroid of area method. The Centroid of Area method is defined by the following equation:

$$z^* = \frac{\int_a^b z \cdot \mu_{c'}(z)dz}{\int_a^b \mu_{c'}(z)dz} \quad (2)$$

where: Z^* is the crisp output value resulting from the defuzzification process. z represents the output variable over its universe of discourse. $\mu_C(z)$ is the membership function of the fuzzy set resulting from the inference process, defínced over the outpat universe $[a, b]$. The numerator $\int_a^b z \cdot \mu_c$ (z) dz calculates the moment of the fuzzy set about the origin, essentially finding the "weighted average" of the output variable where the weights are the degrees of membership. The denominator $\int_a^b \mu_{C'}(z)dz$ calculates the area under the membership function curve of the fuzzy set.

To this end, this method was selected for defuzzification due to its ability to provide a representative and precise output by calculating the weighted average of the output universe, factoring in the degrees of membership of the fuzzy set. In addition, it ensures accuracy by considering the entire output membership function and offers robustness against outliers, thereby producing stable and reliable results. Furthermore, this method was selected due to its precision in representing the outcome of a fuzzy inference process [55]. The model's IF-THEN statements were developed from interviews with construction industry experts working in the O&G construction projects. Consensus among experts

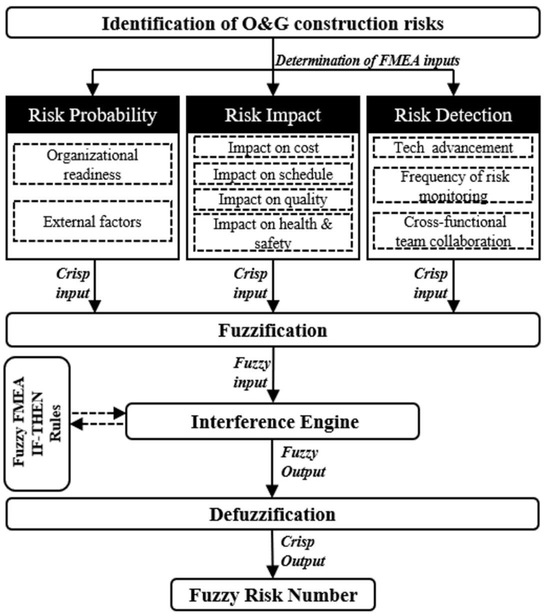

FIGURE 1. Fuzzy model FMEA process.

required a minimum fuzzy panel sample size of four, as recommended by [19]. Accordingly, we conducted interviews with five construction experts in the U.S. Four rounds of online interviews with these experts were conducted to achieve consensus. The data used as inputs in the developed assessment model were obtained through questionnaire surveys. The authors administered a survey to 100 project managers working in O&G construction projects in the U.S. to rank the RP, RI, and RD of the identified O&G risks based on a ten-point Likert scale, ranging from 1 (indicating very low) to 10 (indicating very high). Upon completing the analysis, we further discussed the results with nine project managers who had participated in the semi-structured interviews, utilizing a follow-up open-ended survey. The survey aimed to delve deeper into the root causes of significant risks, as identified in the assessment outputs, and to propose mitigation strategies for these risks. Additionally, it focused on evaluating the developed risk assessment model in terms of: (1) its ease of use; (2) its scalability to accommodate projects of varying sizes and complexities; and (3) its practicality and adaptability.

VI. RESULTS AND ANALYSIS

A. PROFILES OF THE SEMI-STRUCTURED INTERVIEWS

As indicated in Step One of the adopted research methodology, the authors conducted semi-structured interviews with nine U.S. project managers specializing in O&G construction projects. The demographic analysis of the interview participants indicated that two interviewees (22.22%) had 6-15 years of experience in O&G construction projects, while the remainder of the interviewees, seven experts (77.78%), had 16-25 years of experience in O&G projects. Moreover, the analysis revealed that six interviewees (66.67%) held a bachelor's degree, while three interviewees (33.33%) had a master's degree. Furthermore, in terms of memberships in recognized professional bodies, the analysis revealed that all the interviewees were members of the American Society of Civil Engineers.

B. PROFILES OF THE SURVEY RESPONDENTS AND RESPONSE RATE SUFFICIENCY

A sample of 100 online surveys was distributed to U.S. project managers specializing in O&G construction projects. Of these, 78 responses were received. Further analysis showed that 71 of these responses, constituting 71%, were adequately complete and detailed for in-depth analysis. Review of the data indicated that approximately 18.31% of the respondents had 1 to 5 years of experience, 43.66% had 6 to 15 years, 35.21% had 16 to 25 years, and 2.82% had more than 25 years of experience as it can be shown in Figures 2 and 3. Furthermore, the demographic analysis revealed that the survey participants had diverse academic qualifications: 87.32% held a bachelor's degree, 11.27% had a master's degree, and 1.41% had a doctoral degree. The authors evaluated the sufficiency of the data collected from 71 respondents by empirically assessing prior studies. In the construction industry, there has historically been a hesitancy to participate in surveys, as noted by [56]. However, numerous investigations have established baseline sample sizes and satisfactory response rates for survey-based studies in the construction field. For instance, [57] recommended 30–50 respondents, and [58] suggested 25–75 respondents. In terms of response rates in construction-related survey research, [59] pointed out that typical response rates generally range from 25% to 35%, a range that was also highlighted by and [60]. Based on the aforementioned information, it is evident that the obtained response rate of 71% from the respondents exceeds the minimum recommended sample size and survey response percentage commonly used in construction-related empirical studies, thus indicating a robust and reliable dataset for our study Based on the aforementioned information, it is evident that the obtained response rate of 71% from the respondents exceeds the minimum recommended sample size and survey response percentage commonly used in construction-related empirical studies, thus indicating a robust and reliable dataset for our study.

C. IDENTIFIED AND QUANTIFIED O&G CONSTRUCTION PROJECT RISKS

The semi-structured interviews conducted with nine project managers working on U.S. O&G construction projects resulted in the identification of 41 key risk factors. These were classified under six categories, namely: management risks, technical and quality risks, financial and economic risks, health, safety, and environmental risks, legal risks, and stakeholder risks, as presented in Figure 3. Following the identification of O&G risks, the authors quantitatively

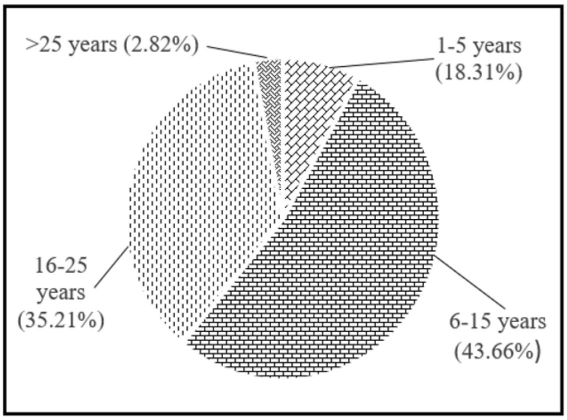

FIGURE 2. Participants' experience years.

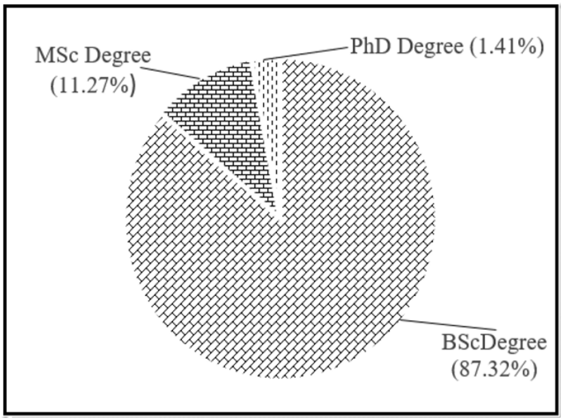

FIGURE 3. Participants' educational background.

analyzed their level of riskiness under Fuzzy-based FMEA environment. The architecture of the proposed Fuzzy-based risk assessment model comprises four fuzzy controllers, as depicted in Figure 8. The first fuzzy controller calculated the risk probability of occurrence, with inputs or and ef, subsequently producing a calculated RP for each O&G risk occurrence as its output. In addition, the second fuzzy controller calculated the level of impact of O&G risks, with inputs ic, is, iq, and ihs, resulting in the calculated RI for each O&G risk factor. Furthermore, the third fuzzy controller calculated the risk detectability, with inputs ta, frm, and ctc, resulting in the calculated RD for each O&G risk factor. Finally, the fourth fuzzy controller calculated the overall level of riskiness of each O&G risk factor by using the outputs of the first three fuzzy controllers to generate a FRN for each risk factor. The developed model employed a trapezoidal membership function to fuzzify its inputs. The inputs and outputs of the model were established using a ten-point Likert Scale and linked to five trapezoidal membership functions for every assessment criterion, as illustrated in Figure 8. In addition, 250 IF-THEN conditional statements were developed under the Mamdani interference system. The FRN for each O&G risk factor was then calculated by applying the centroid of area method to defuzzify the output membership function. The quantified FRNs for O&G construction risks, along with their rankings, are displayed in Table 2. The fuzzy inputs alongside their corresponding membership functions of the developed model, the rules, and their display are presented in Figure 7. The graphical display of the riskiness surface for the O&G risk level controller is presented in Figure 8. This colored mesh grid illustrates how the FRN value varies across different assessment dimensions. The intensity of the color corresponds to the level of riskiness, with darker hues indicating higher risk. The x-axis, labeled "Impact," represents the severity or magnitude of potential consequences, ranging from 0 to 1. An impact level of 0 implies no impact, while a level of 1 denotes maximum or catastrophic impact. The y-axis, labeled "Probability," also spans from 0 to 1, where a level of 0 means the event is impossible, and a level of 1 suggests certainty. The z-axis denotes the "FRN," a composite measure incorporating the probability, impact, and detection of a risk factor. The FRN values range from 0, indicating no risk, to 1.0, signifying extreme risk. The developed Fuzzy-based FMEA model offers significant advantages in handling the uncertainty inherent in OG construction projects. The key advantage of the model is its ability to represent uncertain variables effectively, which is crucial in the dynamic OG environment where risks can emerge unexpectedly due to factors like regulatory changes and market fluctuations. Furthermore, the model facilitates linguistic representation, incorporating qualitative descriptions and expert knowledge into the assessment process, thereby enhancing interpretability for stakeholders with varying expertise levels, a key limitation that exists in traditional risk assessment methods like risk probability and impact matrices. This linguistic approach enables domain experts to express risk factors in their own terms, ensuring a more detailed and comprehensive understanding of the risk landscape. Additionally, the developed model provides flexibility in modeling complex relationships between risk factors, allowing for a more comprehensive assessment and adaptation to different project contexts. In OG construction projects, where risks are often interconnected and influenced by numerous variables, this flexibility is particularly valuable. However, challenges such as the subjective nature of defining the membership functions and the conditional statements of the model pose obstacles, as their selection significantly impacts assessment outcomes. To ensure the reliability and consistency of the developed membership functions and conditional statements, they were carefully designed with reference to prior work (e.g., [61], [62], [63], [64]).

D. VALIDATION AND VERIFICATION

In this research, we conducted open-ended surveys with nine project managers working on U.S. O&G construction projects to validate and verify the developed Fuzzy-based risk assessment model. Three distinct criteria were employed to assess the developed Fuzzy-based risk assessment model: ease of use, scalability, and practicality and adaptability.

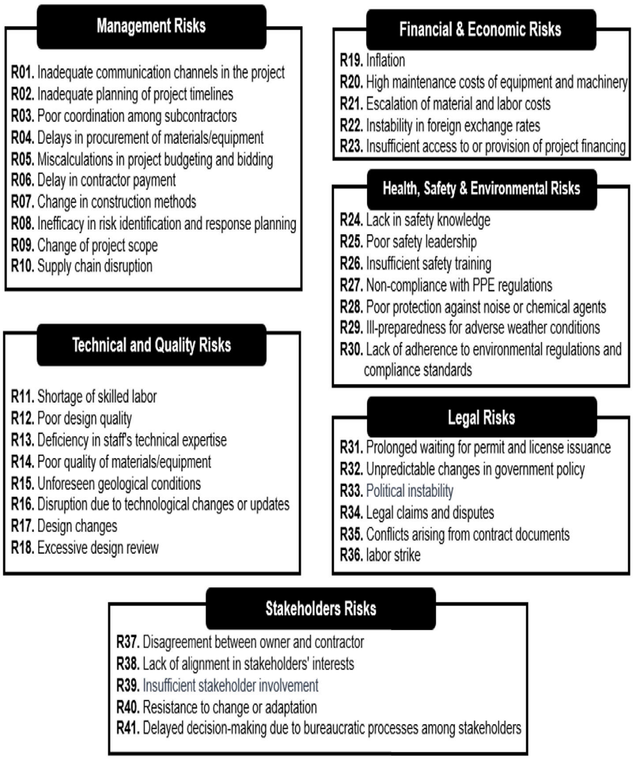

FIGURE 4. Identified and classified O&G risks.

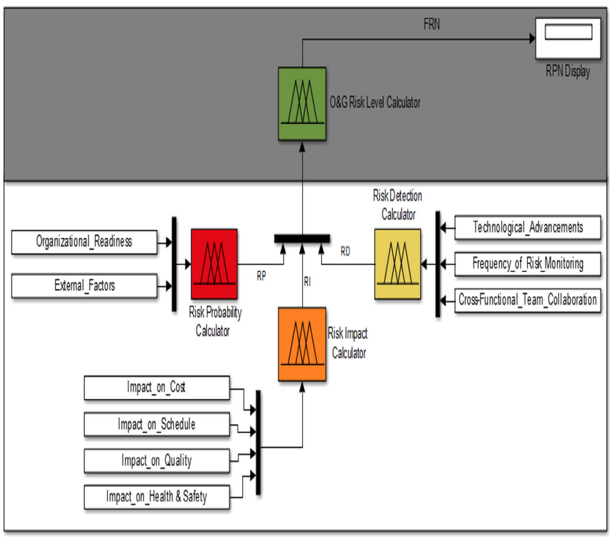

FIGURE 5. Combined fuzzy model architecture.

The practitioners reached a consensus that the model is easily comprehensible and interpretable, offering flexibility that allows for customization to reflect the characteristics of risks associated with O&G construction projects. Moreover, the participants identified the developed model as scalable, highlighting its ability to accommodate diverse scales and complexities of O&G construction projects. Furthermore, all participants affirmed the practicality of the developed assessment models for O&G projects in the U.S., and they emphasized the adaptability of the assessment models,

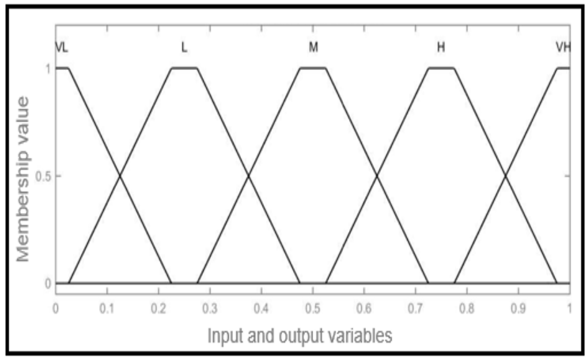

FIGURE 6. Membership functions for risk probability, impact, detection, and FRN.

signifying their capacity to effectively incorporate additional risks and assessment criteria.

VII. DISCUSSION

After completing the Fuzzy-based FMEA analysis of the key OG construction risks, the assessment findings were further discussed through open-ended surveys with nine OG project managers in the U.S. to identify the root causes of significant risks. The following subsections provide details on the top six OG risk factors, ranked from highest to lowest in significance:

A. R27 (NON-COMPLIANCE WITH PPE REGULATIONS)

R27 refers to the failure in adhering to established PPE regulations. This can include scenarios where workers do not wear the mandated safety gear, such as helmets, safety glasses, gloves, or protective clothing, which are essential for ensuring safety in hazardous working environments [65]. The analysis results indicated that R24 possessed the highest level of riskiness among the evaluated risk factors, with an FRN value of 0.581. The experts surveyed attributed the root causes of this risk factor to an inadequate safety culture within organizations. They noted that the importance of safety measures might be underestimated or overshadowed by the pursuit of operational efficiency and cost-effectiveness. This issue is further exacerbated by insufficient enforcement of safety regulations, which allows casual attitudes towards the use of PPE to persist. Other contributing factors identified include a lack of awareness or understanding of the risks involved, poor communication of safety protocols, the perceived inconvenience or discomfort associated with PPE use, and a lack of active leadership commitment to safety practices. To mitigate this risk, the surveyed experts called for a thorough implementation of safety regulations, stressing the importance of not only establishing these rules but also ensuring their strict adherence. They also highlighted the importance of regular safety training sessions to reinforce the significance of PPE and safety measures in the workforce's mindset. Additionally, they recommended fostering an organizational culture that consistently prioritizes safety over expedience or cost reductions.

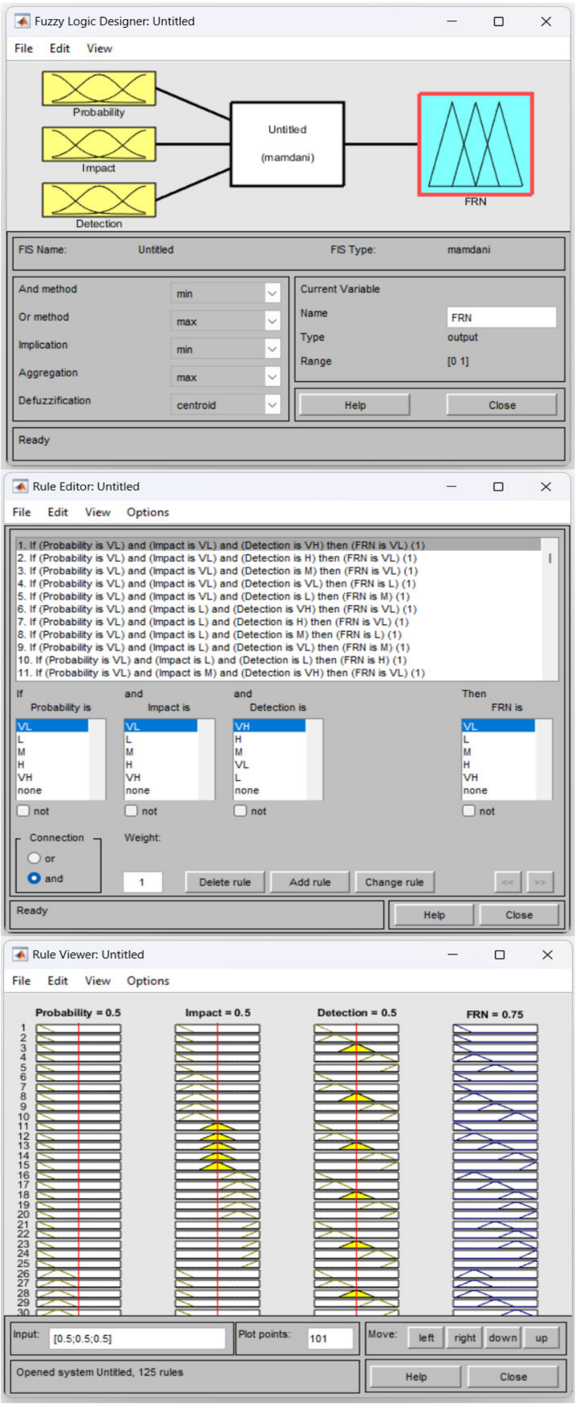

FIGURE 7. The initial figure illustrates the fuzzy inputs alongside their corresponding membership functions. The subsequent diagram delineates the rules, while the third diagram displays the active region of decisions.

B. R01 (INADEQUATE PROJECT COMMUNICATION)

R01 refers to the deficiencies or shortcomings in the communication practices within project teams. Inadequate communication in O&G construction projects can lead to a variety of negative consequences, such as misunderstandings about project requirements, delays in project timelines, safety hazards due to unclear instructions, and overall inefficiency in operations [66]. The results showed that R01 holds the second-highest rank in significance, having an FRN value of 0.568. The surveyed experts identified several root causes for this risk factor, including poor communication planning, a lack of clear communication channels, insufficient stakeholder engagement, cultural and language differences among diverse workforces, and the technical complexity of the information that needs to be communicated. To mitigate this risk, experts emphasized the need for a well-structured communication strategy that incorporates regular project meetings, clear documentation, and the use of collaborative project management tools to ensure that all project stakeholders are consistently aligned and informed, thereby reducing misunderstandings and potential project delays.

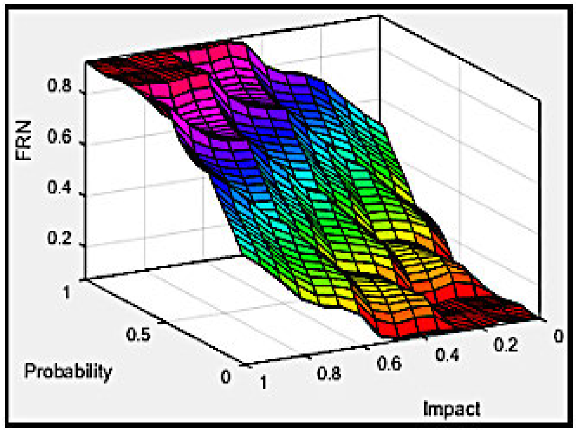

FIGURE 8. FRN riskiness surface.

C. R35 (CONFLICTS ARISING FROM CONTRACT DOCUMENTS)

R35 refers to discrepancies, contradictions, or inconsistencies found within the contract documents related to the project. The presence of such conflicts in contract documents can lead to significant legal and operational issues [67]. This includes disputes over the interpretation of contract terms, challenges in enforcing contractual obligations, and difficulties in managing project execution in line with the agreed terms [68]. The analysis revealed that R35, with an FRN value of 0.529, ranks as the third most significant risk factor. According to surveyed experts, the root causes of these conflicts are ambiguity in language, inadequate details or specifications, multiple document references, regulatory or compliance changes, misalignment between specifications and project scopes, or contradictions between contractual obligations and actual project requirements. To mitigate the risk, the surveyed experts emphasized the need for clear, precise language in contract drafting and the inclusion of comprehensive, detailed specifications to avoid ambiguities. The experts also pointed out the necessity of pursuing regular updates to ensure compliance with evolving regulatory standards and receding the contracting gaps. They underscored the significance

TABLE 2. Quantified levels of riskiness and rankings for O&G risks.

Risk Category	O&G Risk Factors	*Probability*		*Impact*				*Detection*			*FRN*	*Group Rank*	*Overall Rank*
		or	*ef*	*ic*	*is*	*iq*	*ihs*	*ta*	*frm*	*ctc*			
Management Risks	R01	0.56	0.45	0.63	0.82	1	2	0.71	0.56	0.66	0.568	1	2
	R02	0.42	0.61	0.67	0.82	6	19	0.44	0.49	0.22	0.360	6	19
	R03	0.39	0.57	0.74	0.71	8	24	0.28	0.17	0.39	0.329	8	24
	R04	0.43	0.52	0.62	0.81	2	7	0.24	0.28	0.43	0.473	2	7
	R05	0.36	0.65	0.88	0.64	10	30	0.44	0.22	0.29	0.301	10	30
	R06	0.54	0.46	0.68	0.76	5	18	0.49	0.33	0.17	0.367	5	18
	R07	0.38	0.41	0.52	0.58	9	27	0.33	0.27	0.38	0.306	9	27
	R08	0.57	0.62	0.61	0.71	3	8	0.25	0.37	0.24	0.469	3	8
	R09	0.43	0.64	0.43	0.47	4	11	0.23	0.25	0.35	0.412	4	11
	R10	0.61	0.57	0.49	0.52	7	20	0.42	0.19	0.17	0.358	7	20
Technical and Quality Risks	R11	0.52	0.65	0.58	0.83	2	5	0.29	0.25	0.24	0.496	2	5
	R12	0.38	0.33	0.73	0.68	4	17	0.19	0.4	0.23	0.371	4	17
	R13	0.39	0.54	0.64	0.7	1	4	0.44	0.38	0.29	0.523	1	4
	R14	0.47	0.47	0.54	0.52	2	13	0.18	0.3	0.35	0.399	2	13
	R15	0.35	0.43	0.59	0.42	3	35	0.21	0.46	0.41	0.265	3	35
	R16	0.51	0.56	0.65	0.46	3	37	0.43	0.28	0.46	0.252	3	37
	R17	0.46	0.41	0.78	0.75	1	6	0.35	0.41	0.53	0.474	1	6
	R18	0.32	0.44	0.55	0.57	1	33	0.38	0.33	0.24	0.278	1	33
Financial and Economic Risks	R19	0.55	0.68	0.63	0.55	1	25	0.32	0.22	0.19	0.321	1	25
	R20	0.53	0.35	0.78	0.42	3	31	0.25	0.27	0.38	0.291	3	31
	R21	0.49	0.52	0.71	0.56	4	39	0.18	0.41	0.34	0.217	4	39
	R22	0.43	0.36	0.67	0.52	5	40	0.45	0.45	0.18	0.195	5	40
	R23	0.56	0.48	0.62	0.49	2	28	0.47	0.24	0.36	0.305	2	28
Health, Safety, and Environmental Risks	R24	0.52	0.59	0.58	0.63	3	12	0.18	0.39	0.23	0.406	3	12
	R25	0.48	0.31	0.63	0.42	7	29	0.29	0.32	0.19	0.304	7	29
	R26	0.57	0.45	0.64	0.56	6	23	0.28	0.18	0.34	0.331	6	23
	R27	0.66	0.66	0.73	0.84	1	1	0.46	0.27	0.23	0.581	1	1
	R28	0.53	0.41	0.58	0.51	5	16	0.28	0.47	0.47	0.372	5	16
	R29	0.45	0.56	0.64	0.69	4	15	0.24	0.42	0.18	0.372	4	15
	R30	0.54	0.64	0.78	0.67	2	10	0.33	0.24	0.31	0.429	2	10
Legal Risks	R31	0.41	0.58	0.57	0.62	4	36	0.26	0.21	0.38	0.262	4	36
	R32	0.54	0.44	0.60	0.58	2	14	0.17	0.37	0.26	0.381	2	14
	R33	0.22	0.17	0.38	0.31	6	41	0.24	0.35	0.18	0.154	6	41
	R34	0.38	0.31	0.58	0.69	5	38	0.36	0.3	0.36	0.228	5	38
	R35	0.61	0.5	0.78	0.84	1	3	0.28	0.46	0.33	0.529	1	3
	R36	0.59	0.42	0.64	0.71	3	22	0.32	0.29	0.22	0.335	3	22
Stakeholders-related Risks	R37	0.65	0.53	0.51	0.47	1	9	0.22	0.26	0.18	0.469	1	9
	R38	0.54	0.61	0.33	0.54	5	34	0.28	0.19	0.24	0.265	5	34
	R39	0.57	0.29	0.44	0.41	3	26	0.42	0.46	0.27	0.308	3	26
	R40	0.64	0.53	0.39	0.45	2	21	0.45	0.38	0.31	0.356	2	21
	R41	0.51	0.43	0.51	0.58	4	32	0.33	0.37	0.16	0.287	4	32

of effective communication and thorough documentation among all parties involved, alongside advocating for the use of standardized contracts and professional legal reviews. Additionally, they recommended including clear dispute resolution mechanisms within contracts, offering training in contract management, and conducting regular audits and reviews of contracts.

D. R13 (DEFICIENCY IN STAFF'S TECHNICAL EXPERTISE)

R13 refers to the lack of necessary technical skills and knowledge among the project staff, which is crucial for executing the project tasks effectively [69]. According to the analysis results, R13 was positioned as the fourth most significant, as indicated by its FRN value of 0.523. The surveyed experts pinpointed the root causes of this risk factor to a combination of factors: a lack of specialized industry training and exposure leading to a significant knowledge gap about the unique demands and technical complexities of O&G projects, and the rapid evolution of industry standards and technology which often outpaces the consultants' continuous professional development, resulting in outdated practices and approaches. To mitigate this risk, the surveyed experts recommend the provision of regular, targeted training programs designed to keep personal up-to-date with the latest industry developments, technologies, and best practices. Additionally, the experts underscored the significance of investing more in partnerships between consultancy firms and industry bodies to enable the sharing of knowledge and experience more effectively. They also advocated for the establishment of extended mentorship programs, which would serve to bridge the knowledge gap and enhance the spread of expertise throughout the industry.

E. R11 (SHORTAGE OF SKILLED LABORS)

R11 refers to the unavailability of adequately trained and experienced workers required for the project. The findings indicated that R11 had the fifth-highest significance rank, with an FRN value of 0.496. The surveyed experts emphasized that the root causes of R11 stem from a combination of broader market and educational trends, an aging workforce, restrictive immigration policies, and suboptimal working conditions. Suggested mitigation strategies by the experts included investing in workforce development programs, which are crucial for enhancing the skill sets of existing employees and preparing new entrants to the industry with the necessary competencies. Additionally, offering competitive compensation packages was suggested as a pivotal measure to attract and retain top talent, ensuring that skilled workers are motivated and committed to their roles. Furthermore, investing more in establishing collaborations with educational institutions was identified as a proactive step toward nurturing a skilled labor pool; this involves facilitating tailored educational programs, internships, and on-the-job training opportunities, aligning academic curricula with industry needs, and providing students with real-world experience.

F. R17 (DESIGN CHANGES)

R17 refers to modifications or alterations made to the project design during the construction phase, leading to construction delays, as changes may require rework or additional time to implement. Additionally, these changes can increase the overall project cost due to the need for additional materials, labor, and potential disruptions to the planned construction schedule [70]. The analysis results positioned R17 as the sixth most significant, as evidenced by its FRN value of 0.474. The surveyed experts determined that the root causes of R17 risks stem from a combination of evolving project requirements, stakeholder inputs and modifications, technical challenges, regulatory compliance updates, and the incorporation of new technologies. Suggested mitigation strategies by the experts included comprehensive initial planning and design, which are fundamental for setting a clear, detailed project vision and minimizing the need for later modifications. Additionally, adopting flexible project management methodologies was advocated as a crucial approach to accommodate inevitable changes while minimizing their impact, ensuring that the project remains agile and responsive to evolving needs. Consistent and effective stakeholder communication was also emphasized as a pivotal measure for aligning expectations, promptly addressing concerns, and integrating valuable feedback in a timely manner. Lastly, investing in advanced design management tools was suggested as a strategic investment to streamline design processes, enhance coordination among various stakeholders, and facilitate the seamless integration of changes, keeping the project on track and within budget.

In comparing the results obtained with the findings of prior work, it's notable that the identified risk factors echo findings from previous risk management literature on critical infrastructure projects. For instance, R27, concerning non-compliance with PPE regulations, aligns with the conclusions drawn from [65] and, which emphasize the pivotal role of organizational safety culture and enforcement mechanisms in ensuring workplace safety. Similarly, R01's emphasis on inadequate project communication resonates with findings from [15] and [71], underlining the criticality of clear communication channels and stakeholder engagement in mitigating project risks. Additionally, R35's focus on conflicts arising from contract documents aligns with challenges observed in contractual management across diverse domains, as noted by [16] and [72], highlighting the importance of precise language, comprehensive specifications, and effective dispute resolution mechanisms. Furthermore, R13's discussion on deficiencies in staff's technical expertise reflects insights from [73] and [74], stressing the need for continuous training programs and knowledge-sharing initiatives to bridge skill gaps within project teams. Moreover, the observations regarding R11, indicating a shortage of skilled labor, coincide with broader discussions in workforce development literature, as discussed by [17], [75], and [76], advocating for investments in training and educational partnerships to address labor shortages effectively. Lastly, R17's examination of design changes corresponds to findings in construction project management, as noted by [8] and [17] emphasizing the importance of robust initial planning and flexible project management methodologies to accommodate evolving project requirements while minimizing disruptions and cost overruns. These comparisons underscore the consistency of key risk factors across industries and highlight the relevance of leveraging insights from prior studies to inform comprehensive risk mitigation strategies effectively. By drawing parallels between findings in various domains, stakeholders can gain a deeper understanding of common challenges and implement proactive measures to address them, ultimately enhancing project outcomes and fostering resilience in critical infrastructure projects.

VIII. CONCLUSION

This research aimed to enhance risk assessment in O&G construction projects by developing a Fuzzy-based FMEA model, informed by the perspectives of experienced project managers in the U.S. First, semi-structured interviews were conducted with nine project managers working in O&G construction projects in the U.S. to identify the key risks impacting the successful execution and delivery of these projects. Second, a Fuzzy-based FMEA risk assessment model was developed to assess the level of risk associated with O&G construction risks. Third, a survey was administered to and answered by 71 O&G project managers, aiming to rank the probability, impact, and detection dimensions of risk assessment, along with their components, for the identified risks in O&G construction projects. Finally, an open-ended survey was presented to nine O&G project managers to identify the underlying causes of significant risks based on the assessment outputs, propose mitigation strategies for these risks, and verify and validate the assessment model and its outputs. The semi-structured interviews with O&G project managers in the U.S. yielded a list of 41 risk factors classified under six categories. Regarding the six most significant risk factors, the Fuzzy-based FMEA assessment revealed that non-compliance with PPE emerged as the most significant risk factor in O&G construction projects. Following in significance were the risks of inadequate project communication, conflicts in contract documents, design changes, a shortage of skilled labor, and insufficient experience of consultants. To this end, the conclusions of this research be outlined as follows:

- The diverse nature of the identified risks, which range from management and safety to stakeholder-related issues, indicates a need for a holistic and integrated risk management approach—one that considers the interdependence's and collective impact of these risks.
- The results indicate that the most impactful risks influencing O&G in the U.S. are not partial (micro-risks) but rather systemic (macro-risks), and these can be categorized into six distinct categories, as presented in Figure 3.
- Assessing risks using FMEA under fuzzy environment significantly reduced the subjectivity and bias typically found in qualitative data, leading to a more objective assessment framework. The effectiveness of this integration was further improved by capturing the key components across each dimension of FMEA analysis. This examination helps in accurately predicting risk levels by considering factors that influence the probability of risk occurrence, the multidimensional impact of risks once they occur, and the factors affecting risk detectability.
- The quality of the model membership functions and the IF-THEN conditional statements can significantly impact the model outputs, highlighting the necessity for expert knowledge in the formulation of these elements to ensure that the system accurately represents the complexity of the real-world scenarios related to risks in O&G projects.
- The research findings suggest a pressing need for a more focused shift towards a safety-centric culture, within the workplace, with a specific emphasis on improving compliance with PPE guidelines.

Two important questions arising from this study are: how the interdependencies between the identified O&G construction risks can be analyzed and effectively managed to optimize project success, and how can the optimal response strategy for each O&G risk factor be selected from among the alternatives. These questions are crucial, as the complex nature of O&G construction projects often involves interconnected risks, where the mitigation of one risk might influence others, impacting overall project success. The comprehensiveness of the current risk assessment model does not fully explore these interdependencies, presenting an opportunity for future research. Such research should extend beyond individual risk assessment to include the development of advanced models that map out and quantify the relationships between various risks. Additionally, future work should focus on developing optimization models that incorporate industry-specific, risk-based, multi-criteria decision-making for selecting the optimal risk response strategies among alternatives. This future work could greatly benefit from international comparative evaluations and practical applications in real-world projects, which would test and refine these models in diverse operational settings, thereby enhancing the objectivity and effectiveness of risk management in O&G construction projects.

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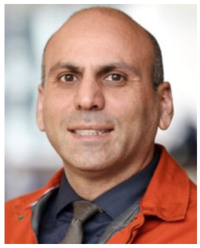

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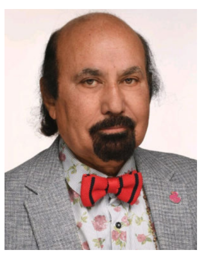

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