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FUZZY LOGIC-BASED QUANTITATIVE RISK ASSESSMENT MODEL FOR HSE IN OIL AND GAS INDUSTRY

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ABSTRACT

The qualitative risk matrix is used in oil and gas industries to evaluate hazard risk related to health, safety, and environment (HSE). Traditional risk matrix processes may enhance the uncertainties in assessing the crucial factors regarding HSE. A better technique is needed to develop in order to overcome these uncertainties. Thus, this study has developed the Fuzzy Logic-Based Quantitative Risk Assessment (FLQRA) model to more accurately assess the HSE risks. In this approach, experts (decision-makers) provide their priority of risk assessment information for the severity of consequences and likelihood of HSE classifications in numerical scaling. Afterward, using a combination of consequence and likelihood associated with each category, the Fuzzy Logic approach is utilized to assess the risk level. MATLAB™ software is used to construct a Graphical User Interface (GUI) model to estimate the quantitative risk level, ranking, and priority for HSE categories according to the calculated risk scores for single and multi-expert inputs. Moreover, the weighted average factor is also introduced to measure the efficiency of experience of the expert in the final risk ranking. The effectiveness of the proposed FLQRA model is evaluated by three different case studies and the results from the model are compared with the existing method. FLQRA model has demonstrated to have the capability to facilitate decision-makers in evaluating the risk involved with HSE in oil and gas industry more effectively.

Keywords: quantitative risk assessment, graphical user interface, fuzzy logic.

INTRODUCTION

Risk assessment has become a challenging task in today's competitive business environment due to uncertainty and imprecision associated with the risk in oil and gas industries. It is widely used to support risk mitigation, prevention, and maintenance for identifying, quantifying, and evaluating the unwanted events or hazards in oil and gas industry. Risk assessment is the process of categorizing and measuring the risk-related outcomes from a specific incident which can be workers' personal injuries, damages related to environment and degradation to assets, which have high effects on the reputation of the industry [1-3]. In order to conduct the risk assessment, an appropriate risk matrix is required to measure the risk level of hazards. Usually, a risk matrix is used to classify which risk is the most critical and provides the methodology to measure the probable impacts of the risk. The risk matrix provides the benefit of risk identification with the combination of the severity of consequence and the probability of the negative effects of an unwanted event [4]. In the existing risk assessment process, three main issues have

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been highlighted. Firstly, this risk assessment process is based on subjective judgment. Due to its subjective nature, the existing process may increase the uncertainty and inaccuracy in risk ranking to select the critical HSE categories; People, Environment, Asset, and Reputation. Secondly, the main issue regarding qualitative risk assessment process is the lack of clarity in the differentiation, which can lead to a problem in selecting the most critical HSE category. The third issue is that the dependency of the results on the experience of the management team.

Generally, the Risk evaluation process in risk assessment matrix is based on the subjective approach to both likelihood and severity of consequences. Dejan et al [5] highlighted that many companies need to carry out a risk assessment, but most of them do not have the experience to determine the risk adequately and suggested a useful risk assessment method as risk ranking matrices that can help to rank the hazards according to their criticality. Furthermore, he states that the risk assessment matrix has its advantages and disadvantages. The qualitative risk assessment matrix process is simple and easy to use, and the risk prioritization can be done simply. This assessment process provides subjective evaluation, due to which the chance of uncertainty increases and lacks granularity (a five-point scale cannot represent a wide range of consequences and likelihoods). Duijm et al [6] state that the risk matrices have two main applications. One application is to perform decision-making about the acceptance of risk and the other is to prioritize which risk needs to be addressed first. Moreover, L. A. Cox et al [7] stress other limitations of the risk matrix that can lead to poor decision making. These include poor resolution, errors in comparative ranking, suboptimal resource allocation, and ambiguous inputs and outputs. To overcome the qualitative risk assessment matrix, the application of quantitative risk assessment method has been suggested. In addition, Elmontsri et al [8] state that the risk evolution can be defined logically with the help of quantitatively axes (Likelihood and Consequence). Moreover, logic-based risk evaluations can facilitate management decisions such as the authorization of operations. It can also help optimize resources by showing where to concentrate efforts for more detailed analysis or risk reduction activities.

Besides being used in decision making, the risk matrix is applied to prioritize which risk needs to be addressed first. Moreover, due to a lack of granularity, when the two risks have the same qualitative ranking, there is no way to rank them based on risk matrix [7]. Another issue with risk matrix is that the matrix does not consider expert knowledge in the risk calculation process. H. Veland et al [9] argue that the risk assessment approaches in the oil and gas industry to measure the risk level do not pay sufficient attention related to expert knowledge and expertise. Furthermore, they assert that the descriptive format used in risk matrix can seriously mislead decision-makers. Hence, the hazards end up with the same assigned risk rank that can lead to risk ties [10].

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METHODOLOGY

The study is divided into two phases. Phase I focuses on data collection, development of the existing risk assessment matrix model, and development of Fuzzy Logic-based Quantitative Risk Assessment (FLQRA) model based on Fuzzy Inference method. Phase II focuses on the development of a Graphical User Interface (GUI) for FLQRA and Fuzzy Logic approach based on multi-expert inputs. Validation of the proposed model is also done in this phase. Figure 1 depicts the research methodology flowchart employed in this study.

DATA COLLECTION

Data Collection: According to Burn and Grove [11], data collection is an accurate systematic gathering of information relevant to the specific objectives and questions of the study. Therefore, a Microsoft Excel-based Risk assessment template has been developed for the data collection from oil and gas industry. Later, the developed template was sent to the respondents in Oil and Gas industry to collect data on the level of hazard risk in three different case studies. Generally, the template is based on the existing qualitative method of risk assessment matrix which is currently followed by industry to assess the overall risk of the hazards or unwanted events. Nevertheless, a quantitative feature is being incorporated into the template. The data collection template has been divided into four excel spreadsheets based on four HSE categories, namely people, environment, asset, and reputation. For each of the categories, five experts/assessors are elicited for both consequence and likelihood. The consequence and likelihood are divided into five attributes namely insignificant, minor, moderate, major, and catastrophic for consequence, and remotely, unlikely, possible, likely, and almost certain for likelihood. The quantitative input range from 0 to 10 has been assigned for both consequence and likelihood. The reason behind the mentioned quantitative scale is to provide an easy assessing method for the expert(s). Although, the quantitative scale can be modified according to industry criteria.

CASE STUDIES

Three case studies have been taken into account to evaluate the risk

Case Study 1: Risk assessment was performed on the damaged equipment vessel. Due to improper lifting method, the failure will occur when the suspended load dropped during lifting. In addition, a loss of mooring could have resulted in the vessel drifting into collision with nearby structures. This may cause significant loss of human lives and natural environmental consequences.

Case Study 2: Risk Assessment was done on the damaged equipment Manifold Control Module (MCM). Generally, MCM is used for the production of oil & gas to provide the

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following well control functions; Activates the production tree from a fail or safe return, activates the safety valves, which are placed in downhole, activates the choked valves, and also helps to control the switching-off the valves, activates of manifolds, which are diverted valves, and shutting off the valves, monitoring the temperature and the pressure of valves, and damaged to the MCM can occur due to strong underwater currents and when the Remotely Operated Vehicle (ROV) hit MCM.

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Case Study 3: The focus of risk assessment is on a damaged subsea manifold. The manifold is a large metal piece consisting of an arrangement of valves or pipes designed to transfer oil and gas from the wellhead. Manifolds are usually mounted on a subsea template and often have a protective structure covering them. The subsea manifold gathers hydrocarbons from several subsea trees that are installed at wells, adjusts the flow, and has the function of sending them to the offshore area through a riser. Typically, Subsea manifold damage was due to a loss in control of high-pressure water jetting during the cleaning process.

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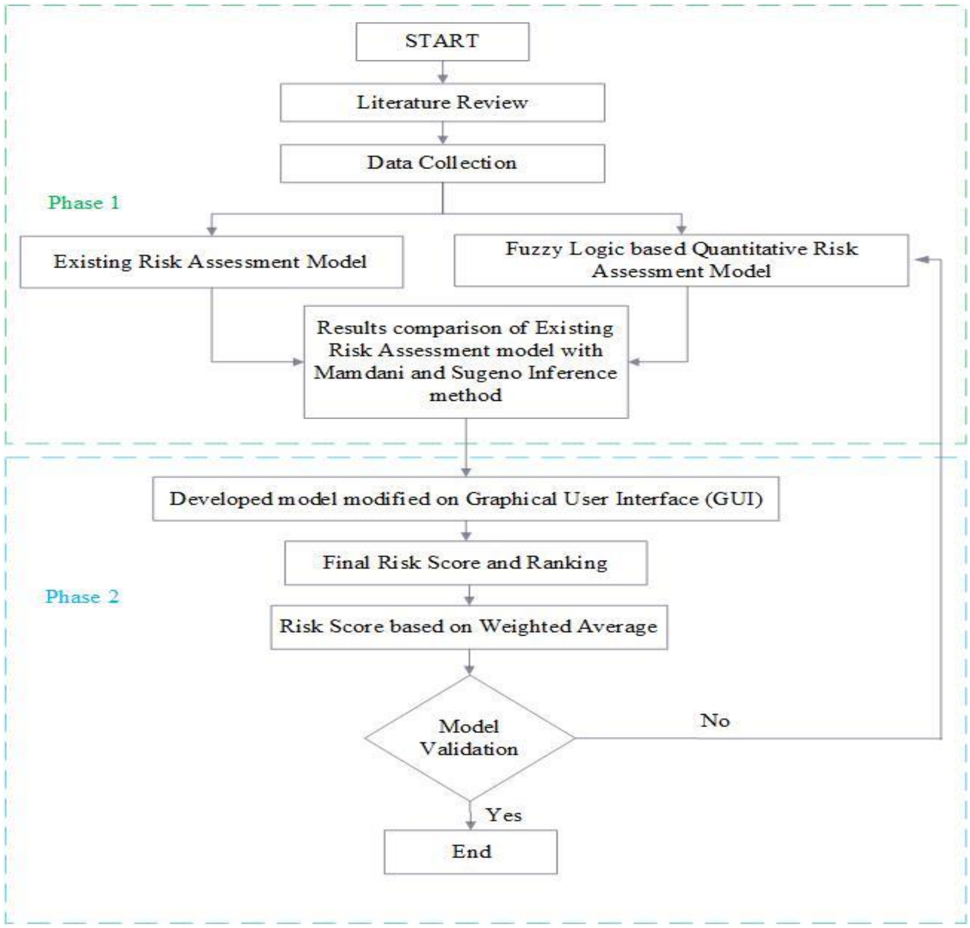

Figure-1. Research Methodology Flowchart

DEVELOPMENT OF FUZZY LOGIC-BASED QUANTITATIVE RISK ASSESSMENT MODEL

The proposed model FLQRA consists of two input variables and one output variable, whereas, the input and output variables are further dissected with five attributes and four attributes. The input variables are represented by; Likelihood and consequence. While the output variable is represented as the total risk. The flow chart of the FLQRA model and the overall structure of FLQRA model is illustrated in Figure 2 and 3.

The obtained data were transferred into a fuzzy number to evaluate the overall risk. In this study, the Mamdani method with Gaussian Membership function with the set of twenty-five aggregation rules has been settled to determine how the risk level changes

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under the different scenarios. The rules in the rule-base are the combination of likelihood, consequences, and total risk. Through utilizing this rule-base with Mamdani implication method, fuzzy results were generated which were defuzzified by using the centroid method in MATLAB R2014a software. Table 1 shows the fuzzy numbers for Consequence, Likelihood, and Risk levels.

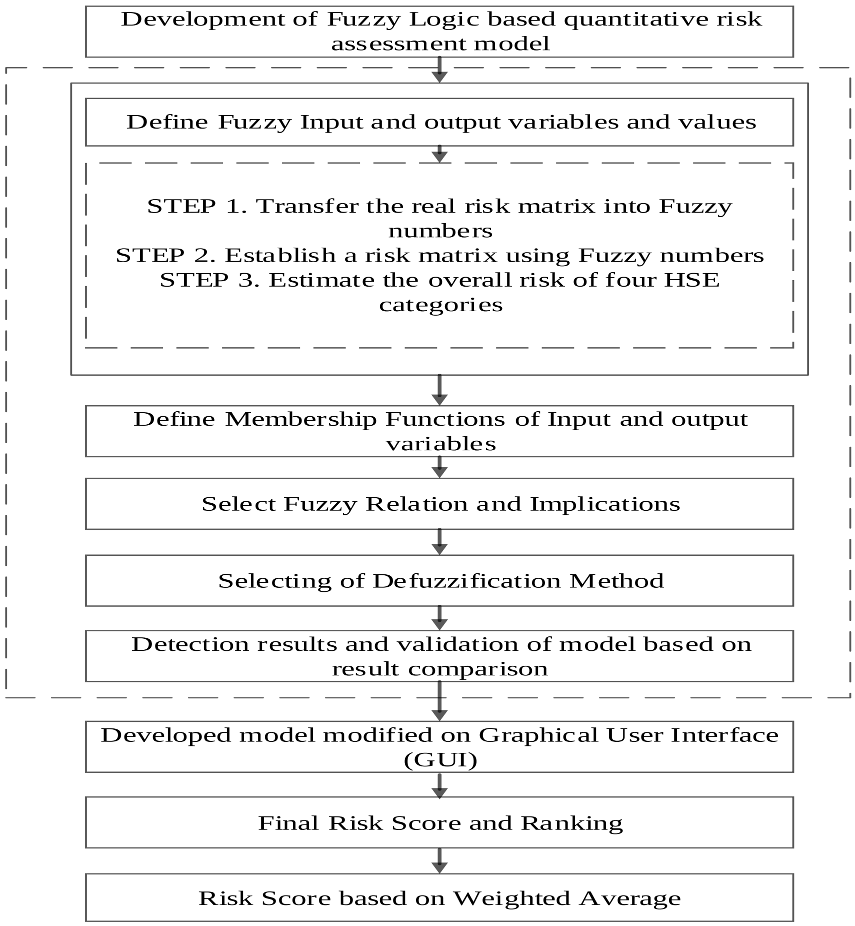

Figure-2. FLQRA model flowchart

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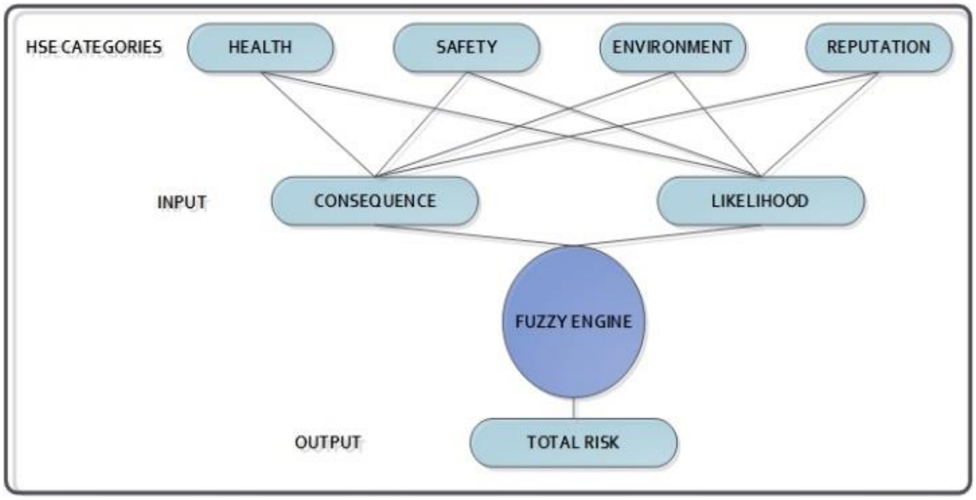

Figure-3. Proposed model inputs and output

Table-1. Fuzzy numbers for Consequence, Likelihood, and Risk

Risk Factors	Fuzzy Set	Range Description
Consequence (C)	Insignificant : 1 Minor : 2 Moderate : 3 Major : 4 Catastrophic : 5	0 < C ≤ 2 2 < C ≤ 4 4 < C ≤ 6 6 < C ≤ 8 8 < C ≤ 10
Likelihood (L)	Remotely : A Unlikely : B Possible : C Likely : D Almost Certain: E	0 < L ≤ 2 2 < L ≤ 4 4 < L ≤ 6 6 < L ≤ 8 8 < L ≤ 10
Risk Category (R)	Low Medium High Very High	1 < R ≤ 25 25 < R ≤ 50 50 < R ≤ 75 75 < R ≤ 100

FUZZY LOGIC MODEL COMPARISON

To establish the Fuzzy Logic model, two different types of inference systems namely Mamdani and Sugeno are applied. For each system, membership functions of Triangular, Trapezoidal, and Gaussian with input and output variables are tested. The results of each inference system with different membership functions were compared concerning the

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original existing risk assessment method results to determine the best method for the proposed FLQRA model.

DEVELOPMENT OF GRAPHICAL USER INTERFACE (GUI)

Once the appropriate method for FLQRA model is determined, a GUI is developed. The idea of developing a GUI for the proposed model was to make it user-friendly, which will contribute to reducing the risk assessment time and the aggregated results based on multi-inputs. With the developed GUI, it is easier for experts to run and assess the proposed FLQRA for validation purposes. By using this GUI, experts or assessors can easily estimate the quantitative risk results, risk priority, and risk ranking of HSE categories; people, environment, asset, and reputation. The interface was created in MATLAB 2014 software. To obtain a more reliable and confident risk score, it is essential to incorporate expert(s) knowledge and experience in the risk assessment process. This expert(s) knowledge and experience support process can be accomplished and simulated by the above-mentioned fuzzy inputs (consequence and likelihood). The developed GUI model provides facilities for expert(s) to change or adjust any fuzzy risk numbers according to the risk score of HSE categories. Figure 4 illustrates the GUI model for risk assessment based on the numbers of experts.

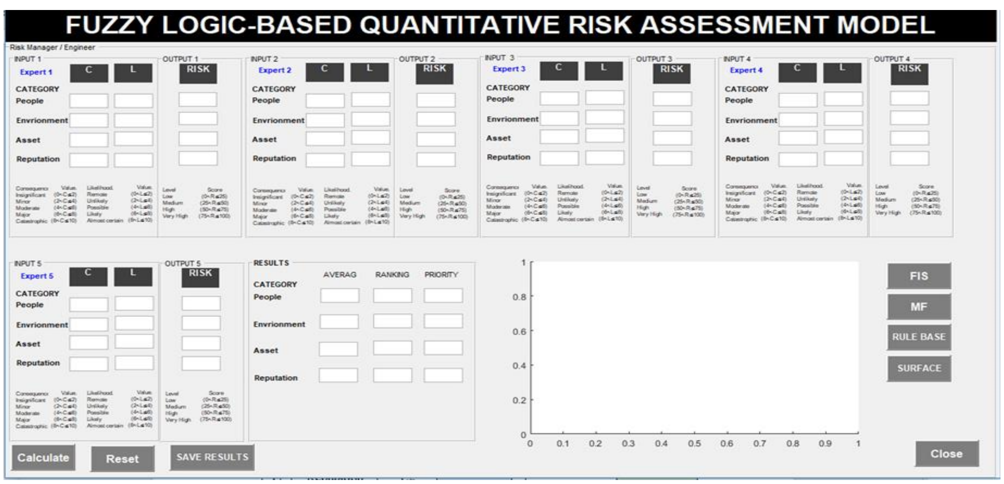

Figure-4 GUI Model

RESULTS AND DISCUSSION

RISK SCORE AND RANKING BASED ON WEIGHTED AVERAGE

The risk analysis is subject to the judgment of the expert based on his experience. Although there are guiding principles to analyze and predict the risk, the experience is a major driving factor in risk analysis. In order to include the effect of the experience of the experts in the overall results, a weighted criterion is introduced in the system, and to

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demonstrate the impact of checking the weighted average for experts, various scenarios are presented. Table 2 describes four different cases that have been developed for this purpose.

Table-2. Description of weighted average cases

Case #	Description
1	All experts are assumed to have the same experience. Hence, there is no weighted score has been assigned.
2	The weighted score has been distributed equally over the range of experience from less than 2 years up to more than 15 years.
3	The team mainly consists of junior experts (3 juniors, 2 seniors).
4	The team mainly consists of senior experts (3 seniors, 2 juniors).

The detailed summary of the above four cases is presented in Table 3.

Table-3. Cases for a weighted average

	Expert	Year	Weighted
CASE-1	**E-1**	NA	NA
	E-2	NA	NA
	E-3	NA	NA
	E-4	NA	NA
	E-5	NA	NA
CASE-2	**E-1**	(< 2)	0.1
	E-2	(3-5)	0.15
	E-3	(6-10)	0.2
	E-4	(11-15)	0.25
	E-5	(> 15)	0.3
CASE-3	**E-1**	(< 2)	0.11111
	E-2	(< 2)	0.11111
	E-3	(< 2)	0.11111
	E-4	(> 15)	0.33333
	E-5	(> 15)	0.33333
CASE-4	**E-1**	(> 15)	0.27273
	E-2	(> 15)	0.27273
	E-3	(> 15)	0.27273
	E-4	(< 2)	0.09091
	E-5	(< 2)	0.09091

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FLQRA MODEL VALIDATION

Model validation is done by getting the experts feedback based on calculated risk assessment results. A feedback form is created and sent to the industrial experts in oil and gas industry for their feedback regarding Fuzzy Logic-based quantitative risk assessment model results. The results which are shared with industrial experts for model validation are based on individual results of three case studies and the comparison of results between the existing method and the proposed model. The analysis procedure is carried out in two phases. The first phase is to measure the risk level of HSE categories based on case studies data and the second phase is to evaluate the final risk score of HSE categories results based on multi-expert input data. The Fuzzy Inference System (FIS) is based on two inference methods; Mamdani and Sugeno Inference System. In order to select the suitable method, the analysis has been conducted by using both Mamdani and Sugeno Methods to calculate the risk of HSE categories by individuals and Cluster. To evaluate the performance of both FIS methods, three types of membership functions are used to calculate the risk level. Based on the literature, Triangular membership and Gaussian membership function are widely used to calculate the risk assessment of hazards. In order to compare the results of all three membership functions in both Mamdani and Sugeno methods, a detailed analysis was conducted in three case studies. While comparing the performances of FIS methods with each other, the best results were obtained from the Mamdani method. To find out more reliable risk results of HSE categories, the analysis of three case studies data of HSE categories; People, Environment, Asset, and Reputation through cluster average is proposed. According to the traditional HSE risk matrix, the risk level is based on four categories; Low, Medium, High, and Very High. For cluster average, some modification has been done with HSE risk level. To calculate the average risk level of HSE category some value has been assigned to existing risk levels. Based on three case studies the Mamdani method with Gaussian membership function has similar results compared to the existing method. Sugeno method, on the other hand, indicated high variance in the results. The main difference between Mamdani and Sugeno was the output membership function. In Mamdani method, the output membership functions can be defined whereas Sugeno has no output membership functions that can be defined. Based on result analysis it is concluded that from Mamdani method with Gaussian membership function provides comparatively better results over other Fuzzy methods and membership functions hence can be used in the proposed FLQRA model.

GUI MODEL RESULTS OF CASE STUDIES

Due to lack of reliability and human error, it was suggested to analyze the data through the developed GUI model. The developed model provides a combination of all 5 experts' input which contributed to a single output result for each HSE category. Moreover, it was

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found that the GUI model worked similarly to the previously discussed Fuzzy Logic model. To obtain a more reliable and confident risk score from Mamdani method, it is important and necessary to incorporate experts' knowledge and experience in the risk assessment process. This expert knowledge and experience support process can be accomplished and simulated by the above-mentioned fuzzy inputs (consequence and likelihood). The developed GUI model provides facilities for experts to change or adjust any fuzzy risk numbers according to the risk score of HSE categories. Figure 5, 6, and 7 shows all three case studies' input values of consequence and likelihood. The values in output boxes show the results calculated using the mathematical calculation process through the developed Fuzzy Logic model. Finally, the result window indicated the calculated risk average, risk ranking, and its priority based on HSE risk score.

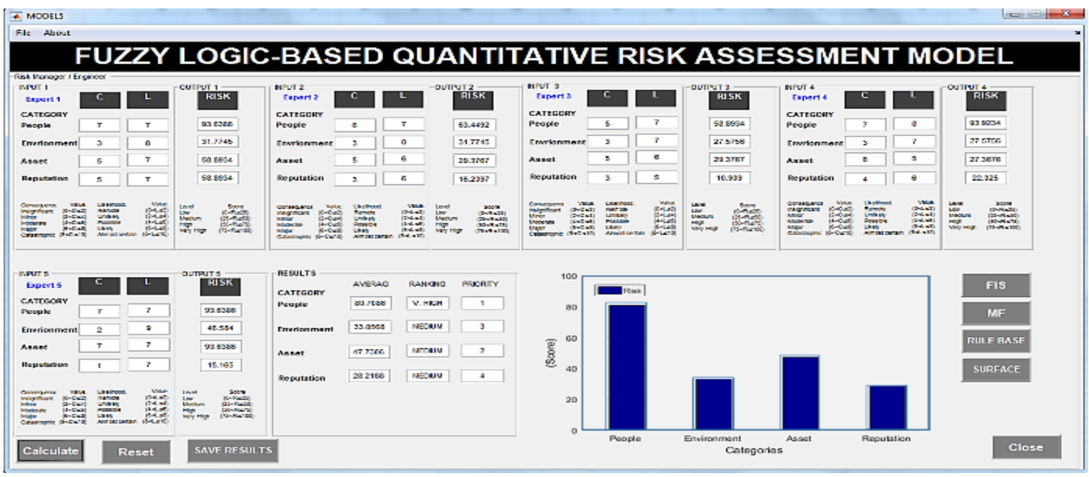
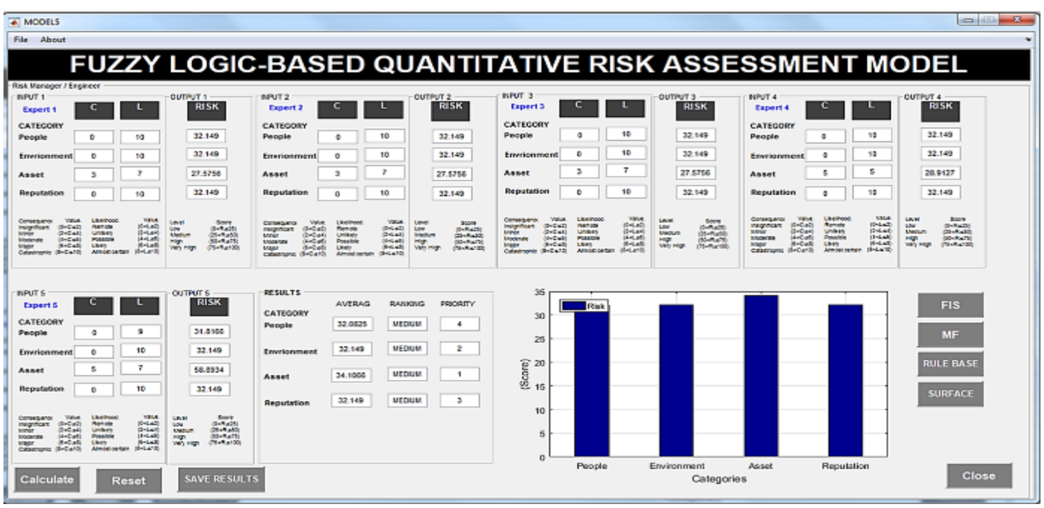


Figure-5 GUI Results for case study 1



Fig**ure-6** GUI Results for case study 2

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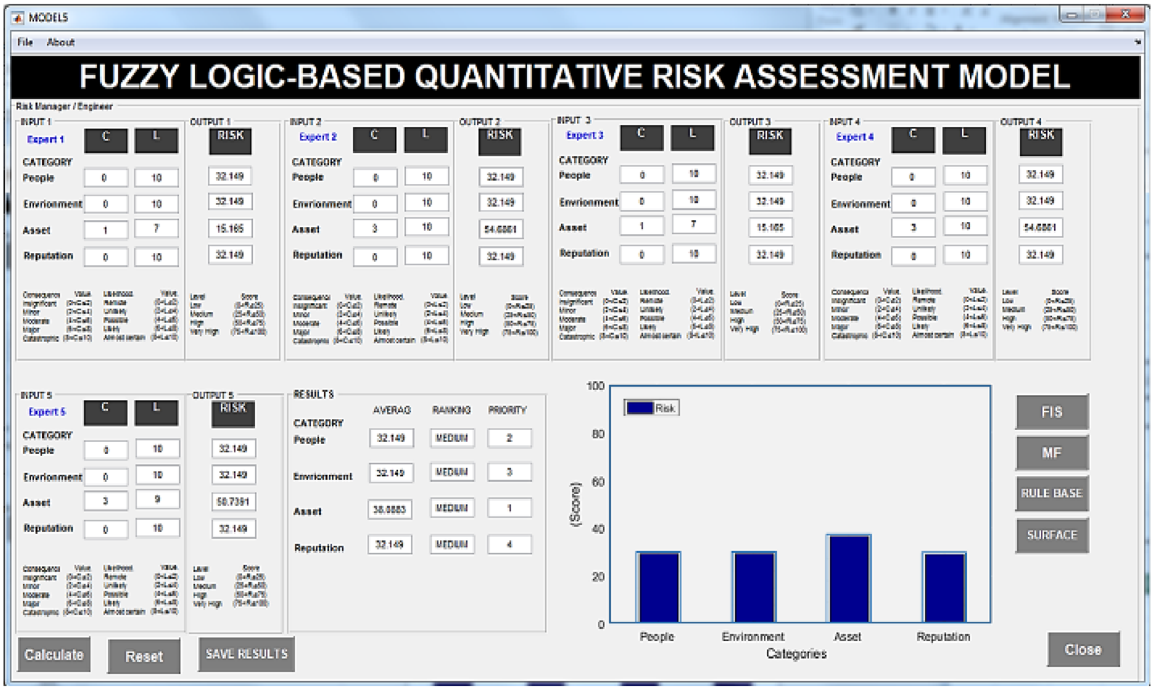

Figure-7 GUI Results for case study 3

In case study 1, the findings assist in prioritizing the HSE categories according to their criticality. The findings indicated that the calculated risk score of 80.70 for the category "People", was the highest-ranked among all categories due to its "Very High" ranking. Based on the table, in terms of ranking, the second rank is an asset, followed by the third environment and the last one reputation. This ranking is feasible in this model due to its quantitative nature, even though all three of them are having the same "medium" ranking. Whereas, in case study 2, the obtained results indicated that the calculated risk score of category "Asset" has the highest ranking among all categories due to its high-risk score, despite all categories having the same "medium" ranking. For case study 3, the calculated risk score of "Asset" is the highest-ranked among all categories, followed by people, environment, and reputation. The Detailed risk ranking for all three case studies regarding HSE factors is shown in Table 4.

Table-4. Calculated average score, risk ranking, and priority of HSE categories for all three case studies

Case	Category	Risk Score	Risk Level	Risk Priority
Case 1	P	80.70	VH	1
	E	33.05	M	3
	A	47.7	M	2
	R	28.21	M	4
Case 2	P	32.08	M	4
	E	32.14	M	2
	A	34.10	M	1
	R	32.14	M	3
Case 3	P	32.1	M	2
	E	32.1	M	3
	A	38.6	M	1
	R	32.1	M	4
P-People, E-Environment, A-Asset, R-Reputation L-Low, M-Medium, H-High, VH-Very High				

RISK SCORE BASED ON WEIGHTED AVERAGE METHOD

One of the issues with risk matrix is that the experience or expertise of the assessors is not fully counted in the assessment process. To overcome this issue, a weighted average method is introduced. In this method, a certain weighted factor has been assigned to each expert based on his or her experience related to the particular working field. To check the sensitivity of weighted average on HSE categories, four scenarios on expert's experience have been applied: equal experience (normal average: base case); diverse experience; mostly juniors and mostly seniors. In case study 1, the results show that when weighted averages are introduced, there is some impact on the risk score, even though the top risk remains in the "people" category. For case study 2, the original top ranking which is "Asset", has been replaced by "Environment" and "Reputation" in scenario 4, when most of the experts are seniors. This major finding demonstrates how experienced experts

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have a significant impact on risk ranking. Whereas, the results of case study 3 are somewhat similar to case study 1. There is no charge for the top ranking. The ranking level is also maintained as “Medium” for all cases. The sensitivity of all four scenarios can be shown in the spider plot as in Figure 8.

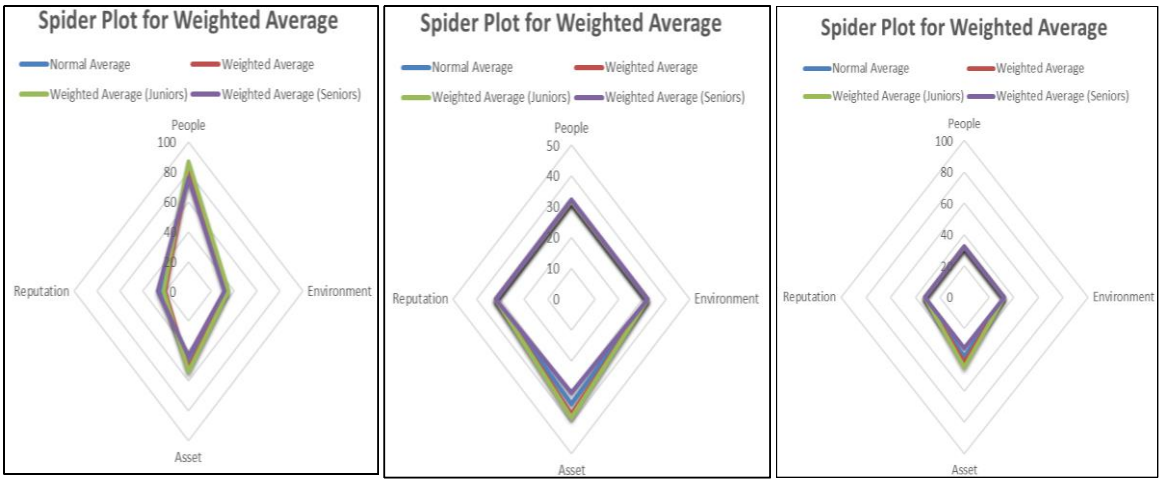

Figure-8. Spider plot weighted average for three case studies

Based on this analysis, it can be concluded that the introduction of a weighted average based on expert experience into the risk matrix has a significant impact on the risk score and risk ranking, hence is worth to be considered in the risk assessment process.

FLQRA MODEL VALIDATION

Validation of proposed model was done by industrial experts. For this, the proposed model was sent along with obtained results from the model and expert feedback form. The target respondents of this study were experts from oil and gas industry with experience and participating in evaluating the risk level of HSE categories. The experts were also asked to provide their demographic information. For this study, four experts agreed to provide validation on the proposed model. Of the total four experts, three were female aged 21 to 30 years while one respondent was male having aged from 41 to 50 years. The designation of two experts was a technical professional, one was managerial personnel and one was engineer/executive. All of them are having experience minimum of five years and above in that field. According to Rubio et al [12]. The exact number of experts needed for consultations depends on the researcher’s own opinion about the feedback opted. Yaghmaei et al [13] assert that it is acceptable even with responses from three experts provided that their opinion reflects the study objective and achieves the aims. The feedback form was based on nine statements as given in Table 5. After gathering the response from experts, further analysis was conducted through Statistical Package for the Social Sciences (SPSS) as it has been considered the most reliable tool

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in social science research. The obtained outcomes from expert feedback show that target industrial experts agreed with the proposed FLQRA model. The findings further suggest that this model can help to provide acceptable quantitative risk assessment results. The experts also agreed that the proposed model can assist in reducing the risk ties among the risk ranking in HSE categories more efficiently. Therefore, the highest rank can be identified easily. Figure 9 shows the experts opinion regarding the FLQRA model.

Table-5. Likelihood categories

No.	STATEMENTS
1	To what extent do you agree that the proposed model will produce an acceptable risk assessment results
2	To what degree do you agree that the proposed model will assist in assessing the risk quantitatively
3	To what extent do you agree that the model will help to select the risk category easily
4	To what extent do you agree that the model will help to resolve to tie among the rank so that the highest rank can be identified
5	To what extent do you agree that the model is easy for an expert to input the data
6	To what extent do you agree that the multi-expert input technique included in the model is useful for Oil and Gas Industry
7	To what extent do you agree that the use of multi-expert input into the proposed model is necessary for a better assessment of HSE risk level
8	To what extent do you agree that the proposed model will help to reduce the processing time in calculating the risk in a team-based assessment
9	To what extent do you agree that the proposed model is adaptable and customizable as per industry requirement

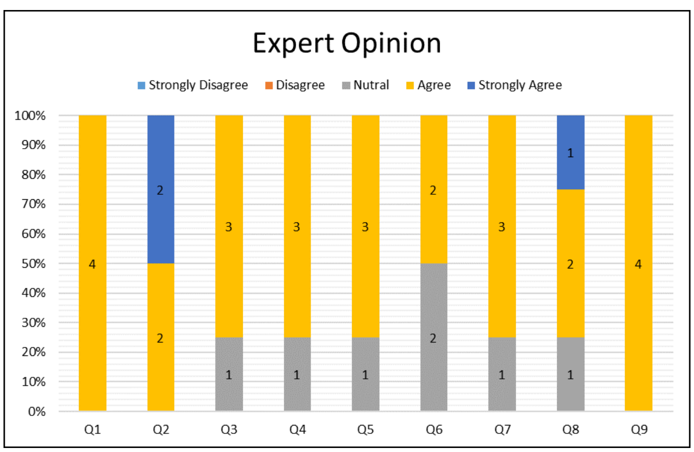

Figure-9. Expert opinion based on model validation

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CONCLUSION

The risk matrix technique is commonly used in oil and gas industry to assess the risk of a potential unwanted event. The qualitative nature of risk matrix and subjective opinion of multi-experts cause the approach to have a high level of uncertainty, particularly in determining the rank of risk and the possibility of a risk-ranking tie. Besides that, the current approach does not appropriately consider experts experience in calculating the final risk. To overcome these issues, this study has proposed the Fuzzy Logic–Based Quantitative Risk Assessment (FLQRA) model. The proposed model was developed based on Mamdani inference system and Gaussian membership function, as they provide comparatively better results than other Fuzzy methods. Based on the proposed FLQRA, the risk assessment results are presented in a quantitative manner and more crisp which enable the risk to be ranked appropriately. As a result, the proposed model reduces the risk-ranking tie condition, hence providing management with better decision making options. Validation of the proposed model was done by obtaining feedback from industrial experts experienced in risk assessment. The proposed model was equipped with Graphical User Interface (GUI) and sent to them for HSE assessment based on three case studies. The GUI helped five experts to simply key in their inputs together and see the risk assessment results easily. The response showed favorable results with experts agreeing that the proposed model is useful in providing better quantitative risk ranking and reducing risk-ranking ties. To take into consideration of experts past expertise and experience in multi-expert's risk assessment process, a weighted average factor has been introduced in the proposed FLQRA. The expert weighted average factor has shown to have some impact on the final risk rank, hence this factor should be considered in any risk assessment process. To demonstrate the impact of the weighted average factor, a few scenarios were presented. The sensitivity analysis has indicated that results can be varied when the weightage and experts experience are changed. Based on this analysis, it can be concluded that the weighted average based on expert experience was a significant impact on the final risk score and risk ranking, therefore worth to be considered in the risk assessment process.

RECOMMENDATIONS

The proposed FLQRA model aims to measure the risk level of HSE for people, environment, asset, and reputation categories in oil and gas industry. Nevertheless, the model can be implemented in other industries with proper modification as per industry requirements. This research can also be extended further by looking at how experts' expertise and experience can be incorporated appropriately into the multi-expert risk assessment process. An in-depth study needs to be conducted to identify the criteria i.e. Education, experience in a related field, position, etc., and determine how to assign properly weight.

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