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ENHANCING RISK ASSESSMENT IN THE OIL AND GAS INDUSTRY: A COMPARATIVE ANALYSIS OF MAMDANI AND SUGENO METHODOLOGIES

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Abstract

Risk analysis is playing a critical role for industries to evaluate and observe the incident/accidents. In today's competitive world industries are focusing on the best solution to evaluate the risk which may leads industry to loss their reputation. This research investigates the application of Mamdani and Sugeno Fuzzy Inference methodologies, incorporating various membership functions, for risk assessment within the oil and gas industry's case studies. The study emphasizes the economic significance of this sector, recognizing its essential role in supporting transportation, manufacturing, and energy sectors, while also addressing potential threats from hazardous facilities. Through a comprehensive Fuzzy Logic-based risk assessment model, with a focus on Mamdani and Sugeno interface systems, the research explores the qualitative and quantitative aspects of risk evaluation. The results indicate the consistent superiority of the Fuzzy Mamdani approach in terms of accuracy and efficiency over the Sugeno method. The model, comprising Likelihood and Consequence input variables and a Total Risk output variable, is evaluated through both qualitative and quantitative analyses. Whereas, the outcomes are based on different membership functions and showcases three case studies, each considering four key factors.

1. INTRODUCTION

The economic significance of the oil and gas sector is integral to any country, offering essential support to transportation, manufacturing, and energy sectors, while also contributing significantly to exports and employment. This industry, alongside facilities like

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fertilizer and petrochemical plants dealing with hazardous chemicals, is exposed to various threats. Evaluating the complete threat scenario becomes crucial before implementing countermeasures. Failure to conduct such an analysis may necessitate treating every potential threat as severe, leading to substantial and inefficient expenditures [1]. Conducting risk assessments in the dynamic realm of contemporary business, especially within the oil and gas industries, presents a formidable task due to the inherent uncertainties and imprecisions associated with these sectors. The widespread adoption of risk assessment practices is integral to supporting comprehensive strategies for risk mitigation, prevention, and maintenance within the intricate landscape of the oil and gas industry [2]. In the realm of the oil and gas sector, the significance of risk assessment and decision-making is widely recognized as a critical aspect. The examination of factors influencing risk assessment plays a crucial role in enabling decision-makers within the industry to effectively address and minimize risk-related challenges, facilitating the implementation of informed decisions concerning risk management [3]. The efficacy of decision-making is intricately linked to the quality of input data and the analytical methodologies applied. In the realm of risk assessment, three predominant approaches come to the forefront: qualitative, semi-quantitative, and quantitative methodologies [4]. Currently, the oil and gas industry employs a qualitative risk assessment matrix to gauge the risk levels associated with Health, Safety, and Environment (HSE) categories [5].

In addressing risks, diverse approaches and methodologies have been developed and embraced. A particularly effective method for mitigating uncertainty and imprecision in risk management is the application of the Fuzzy Logic approach. This approach has found extensive utilization as a methodology in various engineering fields, including civil, industrial, computer, electrical, and mechanical engineering [6, 7]. Fuzzy Logic serves as a systematic tool to address uncertainties and imprecise information within real-world contexts. By employing Fuzzy Logic and methodologies derived from it, the introduction of quantitative input data aids in reducing subjectivity to an acceptable level. The change in perspective is focused on the endeavor to establish connections and dependencies between input data and risk assessment, thereby strengthening control. [8, 9]. The incorporation of Fuzzy Logic, in conjunction with a quantitative risk assessment methodology, has been instituted to support risk managers and experts in conducting a comparative analysis of Fuzzy Logic techniques, namely Mamdani and Sugeno [10-12]. Consequently, within the scope of this research, the utilization of a comparative analysis between Fuzzy Logic Mamdani and Sugeno seeks to enhance the efficiency and rationality of the process for assigning risk levels to specific situations.

1.1 Fuzzy Mamdani and Sugeno Interface System

In its inception, the Mamdani Fuzzy Inference System was originally designed to regulate a combination of steam engine and boiler. It utilized a set of linguistic variables, with the fuzzy rules governing the control system derived from the expertise of experienced human operators. The widespread adoption of the Mamdani method in literature is attributed to its straightforward structure, which involves 'min-max' operations [13]. To

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illustrate, a basic two-input one-output problem, consisting of three rules, is analyzed using the Mamdani method:

Rule 1: If x belongs to A3 or y belongs to B1, then z is assigned to C1.

Rule 2: If x belongs to A2 and y belongs to B2, then z is assigned to C2.

Rule 3: If x belongs to A1, then z is assigned to C3.

The Mamdani fuzzy inference system plays a pivotal role in producing output in a fuzzy format, necessitating the conversion of this fuzzy output into a crisp form. To achieve this objective, various defuzzification techniques are employed to transform fuzzy output into a crisp one.

According to Jang's presentation, five defuzzification methods are recognized, specifically: “Centroid of Area (Z_{COA}), Bisector of Area (Z_{BOA}), Mean of Maximum (Z_{MOM}), Smallest of Maximum (Z_{SOM}), and Largest of Maximum (Z_{LOM})”. Figure 1 illustrates the techniques employed in the process of defuzzification.

In this study, we have employed the Centroid of Area (Z_{COA}) defuzzification method. The ensuing equation offers the mathematical definition of the centroid of area for this defuzzification approach, outlined below:

$$Z_{COA} = \frac{\int_{\overline{Z}}^{+} \mu A(Z)_Z \, dz}{\int_{\overline{Z}}^{+} \mu A(Z)_Z \, dz'} \quad (1)$$

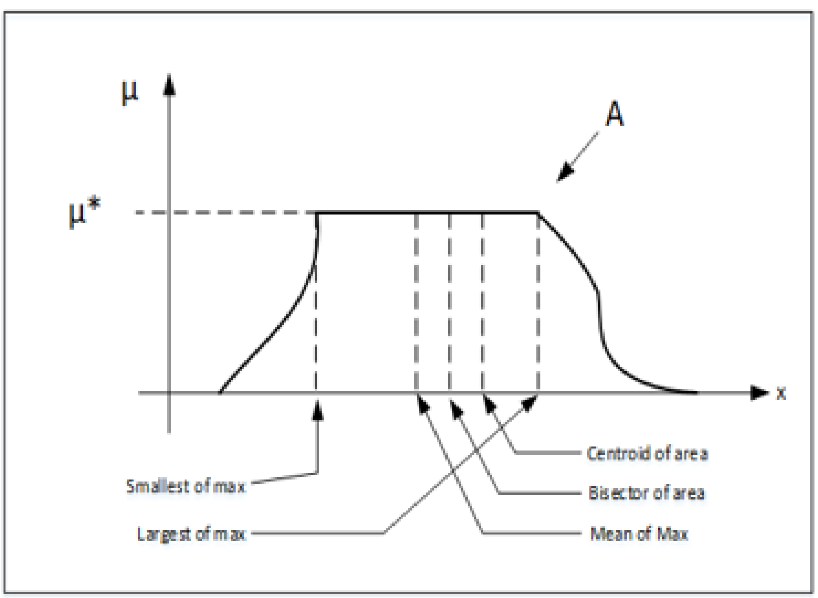

Figure 1: Mamdani defuzzification method

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The Sugeno method, referred to as the second inference system, was introduced with the aim of developing an effective approach for constructing fuzzy rules based on an existing input-output dataset.

A typical rule within a Sugeno model, encompassing two inputs, x and y, and an output, z, is articulated as follows:

$$If\ x\ is\ A\ and\ y\ is,\ THEN\ z\ us\ z = f(x, y) \qquad (2)$$

In the context of this research, the expression *z* = *f(x, y)* represents a deterministic function defining the consequent.

Typically, *f(x, y)* takes the form of a polynomial function involving the inputs *x* and *y*. Nevertheless, it has the flexibility to be any generic function, provided it effectively describes the system's output within the fuzzy region specified in the antecedent of the applied rule [14].

Typically, both fuzzy inference methods, namely Mamdani and Sugeno Inference, undergo a two-step process. The initial step involves fuzzifying the crisp values of input variables into membership functions based on fuzzy sets, a commonality shared by both methods.

However, the divergence between the methods becomes evident in the second step, specifically when integrating the results of all rules into a singular precise output value.

In the Mamdani inference method, If-Then rules are formulated using fuzzy sets, and the output of each rule undergoes reshaping through a matching process. Subsequently, defuzzification is necessary after aggregating all these reshaped fuzzy sets.

Conversely, in Sugeno Inference, If-Then rules are articulated using polynomials with respect to input variables, resulting in the output of each rule being a single numerical value. Notably, Sugeno inference streamlines the process by avoiding the intricate defuzzification step associated with Mamdani inference.

2. METHODOLOGY

2.1 Development of Fuzzy Logic-Based Risk Assessment Model

The presented model comprises two input variables, each encompassing five attributes, along with one output variable characterized by four attributes. These input variables are denoted as Likelihood and Consequence, while the output variable is designated as the total risk.

T Figure 2 to Figure 5 Illustrate visual representation of the fuzzy model representations for Consequence, Likelihood, and Risk level.

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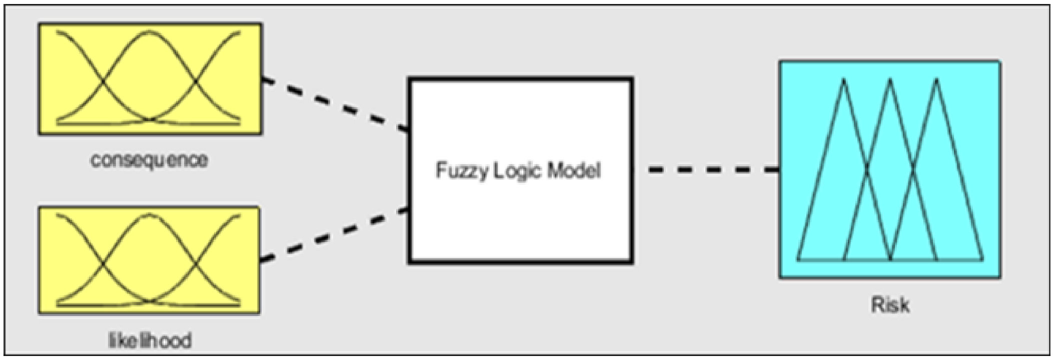

Figure 2: Fuzzy Logic–Based Model

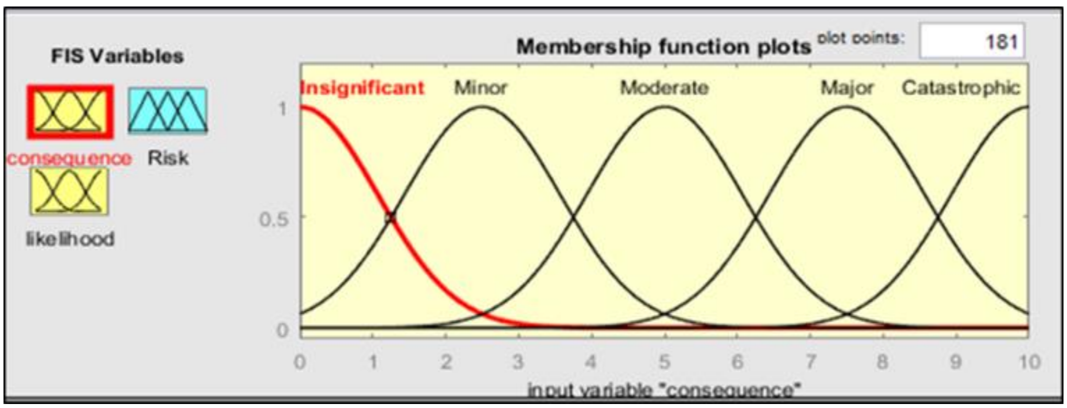

Figure 3: Consequence "Input Membership functions1"

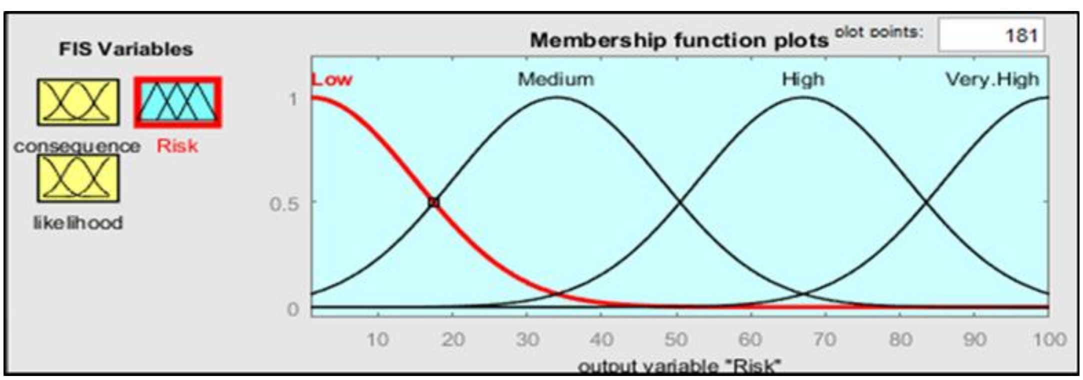

Figure 4: Likelihood "Input Membership functions"

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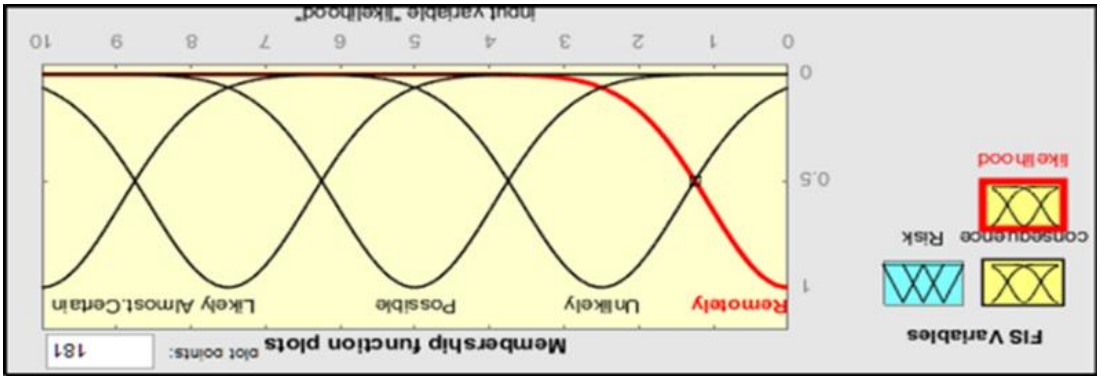

Figure 5: Risk "Output Membership functions"

A collection of twenty-five aggregation rules has been established to assess variations in the risk level across diverse scenarios. The rule-base incorporates combinations of likelihood, consequences, and total risk. This rule-base is then applied utilizing both Mamdani and Sugeno implication methods.

3. RESULTS AND DISCUSSIONS

The findings presented in this study stem from a comprehensive research approach that seamlessly integrates both qualitative and quantitative methodologies. By employing a dual-method strategy, we aimed to provide a holistic understanding of the subject under investigation. Qualitative methods were instrumental in capturing the nuanced aspects and contextual intricacies, offering rich insights into the phenomenon.

Simultaneously, quantitative methods enabled us to analyze numerical data, allowing for a rigorous and systematic examination of patterns and trends. To enhance the robustness of our conclusions, these results were meticulously juxtaposed with those obtained through traditional methods. This triangulation not only validates the credibility of our findings but also contributes to a more nuanced and comprehensive comprehension of the research domain.

The amalgamation of both qualitative and quantitative analyses ensures a well-rounded and reliable depiction of the phenomena under scrutiny, fostering a more comprehensive understanding of the research outcomes. Table 1 represents the qualitative results in the comparison of traditional method with Mamdani and Sugeno method.

Figures 6 to 8 illuminate the dependable outcomes derived from our meticulous comparison of the traditional method with the Mamdani and Sugeno methods. These figures serve as visual aids to underscore the robustness of our findings.

Notably, the analysis reveals that the Mamdani method stands out as the most reliable, yielding superior results when compared to the Sugeno method. Figure 6, Figure 7, and Figure 8 vividly capture the discernible trend, emphasizing the efficacy of Mamdani's approach in generating outcomes that surpass those produced by the Sugeno method.

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This graphical representation not only enhances the clarity of our comparative analysis but also underscores the potential advantages of adopting the Mamdani method in scenarios where reliability and precision are paramount.

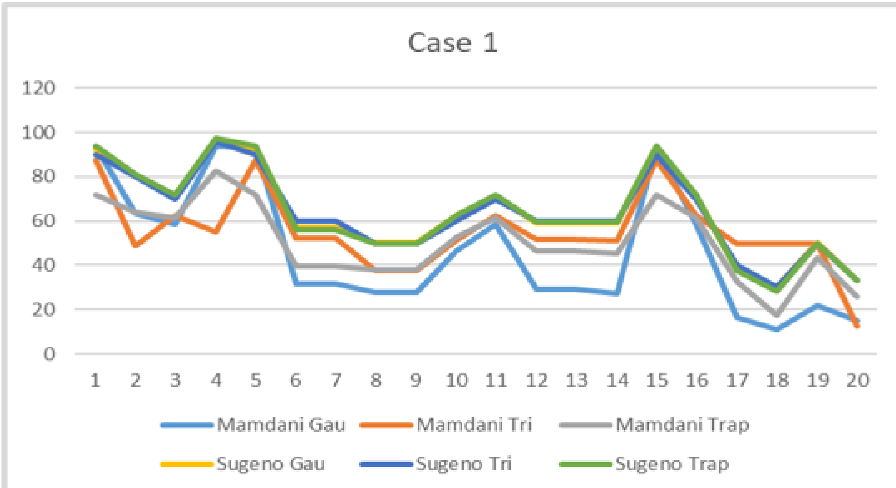

Figure 6: Comparative Quantitative Analysis of Case 1: Traditional Method vs. Mamdani Method vs. Sugeno Method

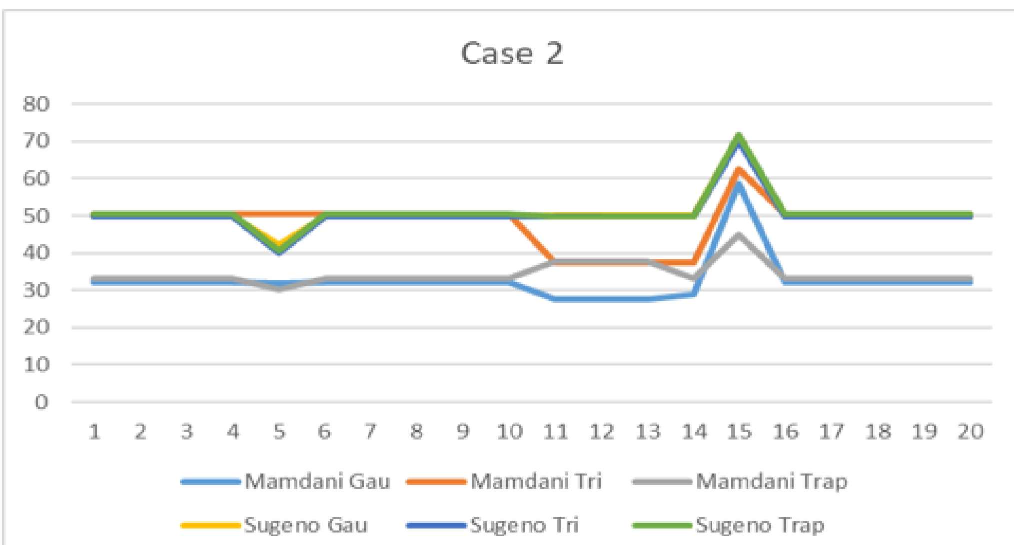

Figure 7: Comparative Quantitative Analysis of Case 2: Traditional Method vs. Mamdani Method vs. Sugeno Method

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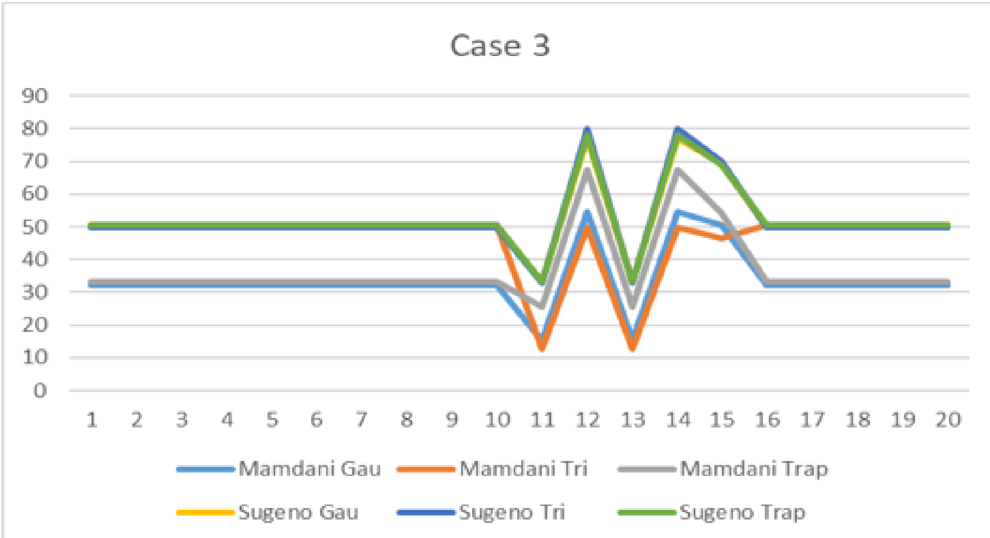

Figure 7: Comparative Quantitative Analysis of Case 3: Traditional Method vs. Mamdani Method vs. Sugeno Method

Table 1 encapsulates the qualitative outcomes arising from the comparative analysis between the traditional method and the Mamdani and Sugeno methods. This table serves as a visual representation of the nuanced insights gleaned from the qualitative examination, offering a comprehensive overview of the distinctions and similarities observed across these methodologies.

The results, based on different membership functions such as Gaussian, Triangular, and Trapezoidal membership functions, add a layer of granularity to the qualitative analysis. Notably, the results presented in Table 1 showcase three distinct case studies, each comprehensively considering four key factors.

Through meticulous scrutiny of Table 1, readers can readily discern the qualitative implications of employing Mamdani and Sugeno methods in contrast to the conventional approach.

The tabulated data serves as a valuable resource for comprehending the qualitative dimensions of the study, facilitating a clearer understanding of the implications and applications of different methods in the investigated context.

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Table 1: Qualitative Comparative Analysis between Traditional Method, Mamdani Method, and Sugeno Method

F#	E#	TR	C#	MR			SR			C#	TR	MR			SR			C#	TR	MR			SR		
				Gau	Tri	Tra	Gau	Tri	Tra			Gau	Tri	Tra	Gau	Tri	Tra			Gau	Tri	Tra	Gau	Tri	Tra
F1	E1	V.H		V.H	V.H	H	V.H	V.H	V.H		M	M	H	M	M	M	H		M	M	H	M	M	M	H
F1	E2	H		H	M	H	V.H	V.H	V.H		M	M	H	M	M	M	H		M	M	H	M	M	M	H
F1	E3	H		H	H	H	H	H	H		M	M	H	M	M	M	H		M	M	H	M	M	M	H
F1	E4	V.H		V.H	H	V.H	V.H	V.H	V.H		M	M	H	M	M	M	H		M	M	H	M	M	M	H
F1	E5	V.H		V.H	V.H	H	V.H	V.H	V.H		M	M	M	M	M	M	M		M	M	H	M	M	M	H
F2	E1	M		M	H	M	H	H	H		M	M	H	M	M	M	H		M	M	H	M	M	M	H
F2	E2	M		M	H	M	H	H	H		M	M	H	M	M	M	H		M	M	H	M	M	M	H
F2	E3	M		M	M	M	H	M	M		M	M	H	M	M	M	H		M	M	H	M	M	M	H
F2	E4	M		M	M	M	H	M	M		M	M	H	M	M	M	H		M	M	H	M	M	M	H
F2	E5	M	CASE 1	M	H	H	H	H	H	CASE 2	M	M	H	M	M	M	H	CASE 3	M	M	H	M	M	M	H
F3	E1	H		H	H	H	H	H	H		M	M	M	M	H	M	M		L	L	L	M	M	M	M
F3	E2	M		M	H	M	H	H	H		M	M	M	M	H	M	M		H	H	M	H	V.H	V.H	V.H
F3	E3	M		M	H	M	H	H	H		M	M	M	M	H	M	M		L	L	L	M	M	M	M
F3	E4	M		M	H	M	H	H	H		M	M	M	M	H	M	M		H	H	M	H	V.H	V.H	V.H
F3	E5	V.H		V.H	V.H	H	V.H	V.H	V.H		H	H	H	M	H	H	H		H	H	M	H	H	H	H
F4	E1	M		H	H	H	H	H	H		M	M	H	M	M	M	H		M	M	H	M	M	M	H
F4	E2	L		L	M	M	M	M	M		M	M	H	M	M	M	H		M	M	H	M	M	M	H
F4	E3	L		L	M	L	M	M	M		M	M	H	M	M	M	H		M	M	H	M	M	M	H
F4	E4	L		L	M	M	H	M	M		M	M	H	M	M	M	H		M	M	H	M	M	M	H
F4	E5	L		L	L	M	M	M	M		M	M	H	M	M	M	H		M	M	H	M	M	M	H

(F-Factors, E-Expert, TR-Traditional Results, C#-Case Study #, MR-Mamdani Results, SR-Sugeno Results, Gau-Gaussian, Tri-Triangular, Tra-Trapezoidal)

4. CONCLUSION

In conclusion, this research underscores the pivotal role of Fuzzy Logic methodologies, specifically Mamdani and Sugeno, in enhancing risk assessment within the oil and gas industry. The Mamdani approach consistently outperforms Sugeno, as evidenced by both qualitative and quantitative analyses. The comprehensive risk assessment model, considering various membership functions and key factors, provides valuable insights for decision-makers in the industry. Mamdani, and Sugeno methods, emphasizing the reliability and precision of Mamdani's outcomes. These findings suggest that adopting the Mamdani methodology can significantly contribute to informed decision-making in scenarios where accuracy and efficiency are paramount. Overall, this research contributes to the ongoing efforts in refining risk assessment practices within the dynamic and intricate landscape of the oil and gas sector.

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