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Failure Mode and Effect Criticality Analysis using Multi-Perspective Fuzzy Rule-Based Method: A Case Study on Refinery Catalyst Slide Valve

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Abstract: Modern industries, particularly oil and gas, robust maintenance management and optimization are vital for increased safety, plant availability, and maintenance cost reduction. The maintenance strategy is therefore crucial, especially under economic pressures on equipment reliability. Failure Mode and Effect Criticality Analysis (FMECA) stands as an important tool in evaluating and mitigating risks within industrial processes, particularly in the domain of refinery operations where safety and efficiency are crucial. This paper delves into the Fuzzy based FMECA methodologies through the incorporation of multi-perspective risk analysis specifically tailored for refinery Fluid Catalytic Cracker catalyst slide valve. This study aims to demonstrate the unconventional multi-perspectives into FMECA by accommodating more risk considerations through case study with input from experts' survey and Fuzzy rule-base analyses.

Keywords: *Failure Mode & Effect Criticality Analysis (FMECA); Fuzzy Logic, refinery valves, Catalyst Slide Valve,*

1. Introduction

Companies use risk analysis to assess any occurrences, breakdowns, or problems that can affect the organization's results [1]. Risk analysis seeks to reduce these unforeseen events in operational, financial, and strategic elements of enterprises, as they can affect any system, product, process, or service [2]. Refinery process control valves are crucial for safe and efficient operations; however, their failure can lead to severe consequences such as production disruptions, safety hazards, and environmental harm. Therefore, the maintenance management of these valves is paramount for production quality, asset longevity, and disaster prevention [3].

Enhancing Failure Mode and Effect Criticality Analysis (FMECA) methodologies for refinery process control valves is crucial to address the multifaceted challenges posed by valve failures. The FMECA process includes steps like identifying failure modes, understanding their effects, calculating the Risk Priority Number (RPN) to rank failure modes, and suggesting corrective measures to prevent failures [4]. Studies have shown that FMECA is a powerful risk analysis technique used to identify and eliminate potential failures, problems, and errors before they occur [5]. FMECA is a prospective risk analysis method that aims to identify the impact of all failure modes in a system, determine their causes, and eliminate or reduce specific ones to prevent issues [6]. While traditional Failure Mode and Effect Criticality Analysis (FMECA) methodologies offer a systematic approach to identifying and addressing potential failure modes of these valves, they often struggle to accommodate the diverse array of considerations inherent in real-world industrial systems [2].

This paper proposes the multi-perspectives risk criteria with integration of Fuzzy Logic into FMECA to surmount these challenges and enhance the accuracy of risk assessment in refinery process control valves. Failure Mode and Effect Criticality Analysis (FMECA) is one of the important assessments in reliability and maintenance is, in which each equipment item is evaluated in detail, considering various failure scenarios and corresponding maintenance strategies. This requires knowledgeable personnel to be able. FMECA ranks within a criticality hierarchy and guides maintenance priorities [7]. However, some reports suggest that failures can occur in components that are initially deemed noncritical [2]. Knowledge-based or expert systems, as discussed by [8], aim to provide expert-level decision support by accumulating specialized knowledge. Recent studies have aimed to improve critical assessment systems for effective maintenance strategies. Researchers agree that the conventional method within FMECA has weaknesses, and lacks precision [2, 9] because it lacks a comprehensive perspective, leading to suboptimal strategies that can impact safety, environmental compliance, and operational costs. The challenge is to develop an improved model that considers multiple risk factors and integrates fuzzy logic to improve criticality assessment for refinery valves, ultimately optimizing their reliability.

2. Literature Review

2.1. FMECA: Concepts and Limitations

Failure Mode and Effects Analysis (FMECA) is a method

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designed to identify potential failures in the design of products or processes [10]. It involves analysing potential project failures, prioritizing these failures, and proposing improvement actions to enhance process reliability and reduce the likelihood of failure [11]. The prioritization is based on three criteria: severity (the impact of the failure on the customer), occurrence (the likelihood of failure occurrences), and detection (the probability of detecting the failure) [12, 13].

FMECA can be applied in four main areas: system, product, process, and service [14]. System FMECA is used in the early stages of project conceptualization, assessing failures in systems and subsystems. Despite its widespread application, FMECA has notable limitations. Criticisms often focus on the calculation of the Risk Priority Number (RPN), which is the product of severity (S), occurrence (O), and detection (D) indices [2]. This number ranges from 1 to 1,000, with higher values indicating higher risk. The criticism lies in the equal weighting of S, O, and D, which may not accurately reflect their relative importance in different industry contexts [15]. Furthermore, the nonlinear scale of occurrence compared to the linear scale of detection complicates the accurate representation of real-world scenarios [2]. For example, a failure mode with occurrence 3 and detection 4 yields an RPN of 12, translating to a failure probability of 30 ppm, whereas occurrence 4 and detection 3 also yield an RPN of 12 but with a failure probability of 100 ppm.

Additionally, the severity factor only considers the consequence to the customer, with no comparable metric for differences between severities of distinct failure modes [13]. The resolution of the RPN from 1 to 1,000 is seen as unrealistic, as only a few values within this range are possible combinations. Moreover, the RPN does not account for production quantity, failure cost, or the effectiveness of risk reduction measures. FMECA also demands significant initial effort and a robust infrastructure of testing, historical data, team experience, and data access, which can be challenging [15, 16]. Additionally, subjective descriptions and relative importance between risk classifications, as well as difficulties in knowledge sharing among different team members, pose further limitations [2, 17].

2.2. Integrating Fuzzy Logic and FMECA

Conventional Failure Mode and Effects Critical Analysis often faces criticism for its difficulty in accurately determining the occurrence of failures and for not considering the relationships between different failure modes [13]. The RPN calculation, derived from severity (S), occurrence (O), and detection (D) , overlooks indirect relationships between these factors [9]. Fuzzy logic offers a potential enhancement by addressing these issues, minimizing subjective judgment effects, and improving decision-making [18, 19]. Integrating fuzzy logic with FMECA transforms the previously linear relationship between S, O, and D into a non-linear one, ensuring that low RPN effects are not overlooked and better modelling the true risk [20-22]. Majority of proposed fuzzy FMECA approaches employs fuzzy if–then rules for prioritization of failure modes [2] The fuzzy inference process involves four steps: fuzzification, evaluation of fuzzy rules, aggregation of fuzzy rules, and defuzzification [9, 10]. Various applications of fuzzy FMECA have been explored in other researched in different industry application such as in oil and gas, aeronautical, aviation, underground coal mining, railway infrastructure, the paper industry, the food cold chain, construction projects, electric vehicle charging, engine manufacturing, marine safety, and wastewater treatment [23]. These studies highlight the utility of Fuzzy FMECA in addressing complex risk analysis challenges across various industries.

2.3. FMECA Fuzzy Risk Analysis in the Oil and Gas Industry

In the oil and gas and petrochemical process industry, risk analysis methodologies, including FMECA, have been applied extensively. Braglia, et al. [9] employs a fuzzy rule based RPN method to improve criticality assessment analysis in manufacturing process plants, suggesting that fuzzy logic is a powerful tool for handling vague and unreliable linguistic evaluations by experts. Bevilacqua, et al. [24] presented the development and application of turnaround risk-based criticality selection in an oil refinery in Italy. The aim is to select the most critical equipment be shortlisted as critical for next maintenance schedule. The good improvement of this study consider is they use non-conventional risk factors as their inputs such as Safety and environmental impact, corrosion sensitivity, warning of technical committee, equipment complexity, impact production, impact on maintenance plan, possibility of spare and failure rate.

Qi, et al. [25] presents a methodological research study on criticality-based maintenance for general process plants, demonstrating the effectiveness of a fuzzy logic-based system compared to conventional systems. The results indicate that the fuzzy logic-based system not only performs the same functions as the conventional system but also outperforms it in terms of reliability and offers a unique ranking capability. However, the paper is relatively simplistic, as it only considers two common risk factors: impact on health and safety and impact of shutdown. While these factors are undoubtedly important, the inclusion of additional risk factors would provide a more comprehensive and accurate assessment of equipment criticality in maintenance management. Despite its simplicity, Qi, et al. [25] contributes to the literature by showcasing the benefits of using a fuzzy logic-based system for criticality-based maintenance in process plants.

Wu, et al. [26] propose a framework utilizing a fuzzy rule-based critical assessment to analyse corrosion failure in refining and petrochemical equipment. Although the authors consider only two main risk factors—likelihood of failure and severity—they include three sub-risk factors under likelihood and four sub-risk factors under severity, which enhances the accuracy of the assessment and provides a more precise outcome of criticality level. Kumar, et al. [27] used fuzzy rule based FMECA combine with Gray Rational Analysis (GRA) to Liquified Petroleum Gas plant equipment risk prioritization. According to them, GRA approach give advantage in case absence of predefined inference rules which require a lot of expertise otherwise.

Yazdi, et al. [28] applied a method called Intuitionistic Fuzzy Analytic Hierarchy Process (IFAHP) combine with Fault Tree Analysis to deal with uncertain data in petrochemical process industries. The method uses only two main risk factors but there is multiple sub risk considered in their AHP model. The model outcome said to be significantly improved the risk analysis with more to safety is the main concern, however, the method required multiple complex analysis and the case study focus on major equipment. This might not be suitable for daily assessment for last number of equipment such as valves and instrumentation. In the context of FMECA applied to valves within the process industry, only two pertinent studies were identified. Sotoodeh [29]applied conducted an FMECA on pipeline ball valves, and Yusof and Abdullah [30] applied FMECA to butterfly valves. Both studies adhered to traditional methodologies without proposing any enhancements to the existing framework.

2.4. Refinery Process Valve

In the oil and gas and petrochemical process industry, risk analysis methodologies, including Petroleum refineries are essential for converting crude oil into usable fuel and chemicals. They have three main sections: separation, conversion, and finishing, which use temperature, pressure, and catalysts, respectively, for different processes. These processes include separation, conversion, and blending, each with unique operations [31]. Valves are one of vital components in refinery process and operations and are responsible for safety isolation, safety release and controlling processes, such as flow, level, pressure, and temperature. Valves serve essential functions, acting as control elements, safeguards for process safety, and contributors to the mechanical integrity of refineries. Failure of valves can have severe consequences, including environmental incidents and safety hazards [32, 33].

Valve failures can lead to release of hazardous substances, safety risks, and loss of revenue [34]. Factors such as the process conditions, operational needs, and degradation contribute to valve failure [35] . To prevent them, refineries use strategies such as predictive, preventive, condition-based, or reactive maintenance, choosing based on cost, and spare part availability for tasks such as replacement, overhaul, modification, repair, or coating maintenance [36]. Valve failures can have far-reaching consequences, making it imperative for refineries to adopt appropriate maintenance strategies based on their specific needs and criticality of the valves in their processes. These strategies help to prevent unexpected shutdowns, reduce repair costs, improve process performance, and ultimately increase profitability [37].

Failures in valve systems can lead to significant safety and environmental issues. For instance, major incident, in 2015, an explosion occurred at the Torrance refinery in California, which was attributed to a failed valve that caused a fluid catalytic cracking (FCC) unit to over-pressurize and explode, injuring four workers and causing extensive damage to the facility [38]. The incidents underscore the importance of effective valve reliability management and maintenance strategies to prevent catastrophic failures in refinery operations, highlighting the need for a comprehensive and strategic approach to criticality assessment and maintenance strategy selection.

2.4.1. Valve Function, Failures and Maintenance Context

There is a scarcity of research specifically addressing the functionality and maintenance of process valves. Most available references are derived from textbooks, industrial standards, industry publications, and data provided by valve manufacturers. Valves control specific process parameters within control loops or act as isolators to block process fluid flow [39]. They vary widely in type, size, pressure class, material, and application, necessitating different maintenance and operational strategies. Common types of valves include ball valves, globe valves, butterfly valves, slide stem valves, among others [39-41]. Valve integrity management is crucial, addressing issues such as leakage, vibration, loss of integrity, and function failures.

Common failure mechanisms include stem seal failure, fatigue, erosion, cavitation-erosion, and corrosion-erosion [37, 42, 43]. Valve failures can be classified into three main categories:

1. Loss of Integrity: Failures in the valve body, seals, or external parts leading to leakage or pressure release.
2. Loss of Intended Function: Failures in operation, such as blockages or actuator failures
3. Loss of Intended Performance: Issues like stiction, causing the valve to operate below performance standards

Valve failures can result from corrosion, seal deterioration, scoring, vibration fatigue, and cavitation. Sticky or seized valves due to high-viscosity fluids or contaminants are common [44]. Valve failures impact process safety and efficiency, leading to incidents such as leaks, inability to isolate hazards, and production losses [3]. Effective valve maintenance can reduce downtime and improve profitability [45]. Common causes of valve failure include inadequate design, material defects, and severe process conditions such as high pressure and temperature, also, external environmental conditions also play a role, necessitating consideration in maintenance strategies [44]. Failure patterns can be categorized into various curves such as bathtub, wear-out, and fatigue, each indicating different failure probabilities over time [46].

Effective valve maintenance is essential for process safety and efficiency. Maintenance strategies must be tailored to the specific failure risks and operational requirements of the valves to ensure optimal performance and reliability. Common maintenance Strategies for valve include [44, 47-49]:

1. Predictive Maintenance: Using diagnostics to predict and prevent failures, reducing unplanned outages
2. Preventive Maintenance: Scheduled maintenance based on reliability characteristics to prevent unexpected failures.
3. Condition-Based Monitoring: Maintenance triggered by real-time condition assessments using sensors.
4. Corrective Maintenance: Reactive maintenance performed after a failure occurs, often costly and high-risk.

Valves can fail in different ways, including the loss of integrity, intended function, or performance. The loss of integrity may result from issues such as erosion, material defects, or wear and tear, causing leakage or pressure release. Loss of the intended function occurs when valve accessories or components, such as positioners or actuators, stop working because of factors such as air blockage or electronic failures. Loss of intended performance involves reduced efficiency due to problems such as increased friction or sticky valve internals [44].

Various factors contribute to valve failure, including extreme process and ambient conditions, operational requirements, and degradation patterns. To prevent these failures, refineries use maintenance strategies such as predictive maintenance, preventive maintenance, condition-based monitoring, and reactive maintenance; choose the appropriate strategy based on factors such as cost and availability of spare parts; and perform tasks such as replacement, overhaul, modification, repair, or coating maintenance as needed [32].

Figure 1 shows the valve maintenance factors mind maps which summarized from various books, report and publications [37, 41, 44, 47, 50]

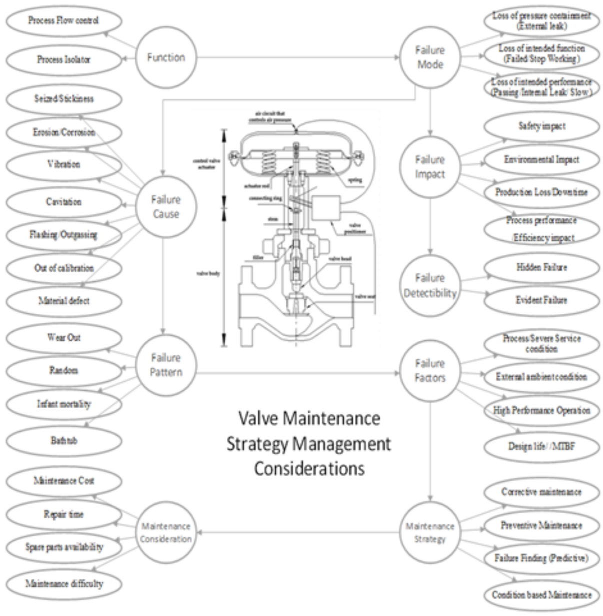

Fig. 1. Summary maintenance factors comprehensive mind maps

3. Methodology

3.1. Fuzzy Criticality Assessment

Fuzzy logic aids complex decision making, offering nuanced degrees of truth, unlike Boolean logic's binary approach. It involves fuzzification, rule evaluation, and defuzzification of gray-area outcomes [2]. When experts vary in perspective, fuzzy logic reduces the uncertainty in maintenance decisions, accommodating human errors [51]. Applied in FMECA, it enhances criticality assessment, supports holistic maintenance analysis especially if considering more perspectives [52]. In this research, fuzzy logic applied individually to various dimensions, each representing the viewpoints of different stakeholders in refinery operations and management

The idea is to represent Fuzzy FMECA factors using linguistic variables and rank them using fuzzy numbers triangular or trapezoidal fuzzy numbers [53]. To do that, the first step is to define membership functions for the risk factors. Once membership functions are defined, each risk factor can be represented by linguistic variables. After that, expert judgment can be collected regarding the three risk factors in the form of linguistic terms. These linguistic terms are integrated in the fuzzy rule base to produce linguistic term representing the criticality number [54]. In particular, a complete if–then rule base may consist of hundreds of rules, where “If” refers to an antecedent that is compared to the inputs, and “Then” refers to a consequent, which is the result/output [55].

3.2. Multi-perspectives Fuzzy Criticality Assessment Model

Kermani [56] and [57] introduced a strategic maintenance multi-criteria model, grouping the perspective into four strategic groups - safety, financial, operational, and technical aspects. This research adapted the Kermani-Labib model as basis of Fuzzy FMECA analysis. Based on the maintenance risk factors determined in section 2, valve maintenance risk factors categorized into four strategic groups as per Kermani Model: operational, safety, technical, and financial perspectives. Table 1 shows the valve maintenance risk factors grouped into the four strategic perspectives as per Kermani-Labib model.

Due to the limitations of time and complexity, this study uses only eight (8) risk factors in the fuzzy critical assessment model. Hence, for each strategic perspective of Kermani-Labib model only two risk factors from each group were considered.

Table 1. Valve maintenance risk factors grouped into four strategic perspectives.

Group	Risk Factors
Operational Perspectives	Failure Rate (Occurrence)
	Severe Process Condition
	High Performance
	External ambient condition
Safety Perspective	Safety Impact (Severity)
	Environmental Impact (Severity)
Technical Perspective	Hidden/Evident Failure (Detectability)
	Failure Pattern
	Spare Parts Availability
	Maintenance difficulty
Financial Perspective	Production Loss
	Performance Efficiency
	Maintenance Cost
	Repair Time

The selection of risk factors is based on a few reasons such as, the important of factors and complexity of evaluation. Selected maintenance risk factors for valves have been evaluated and summarized in Figure 2.

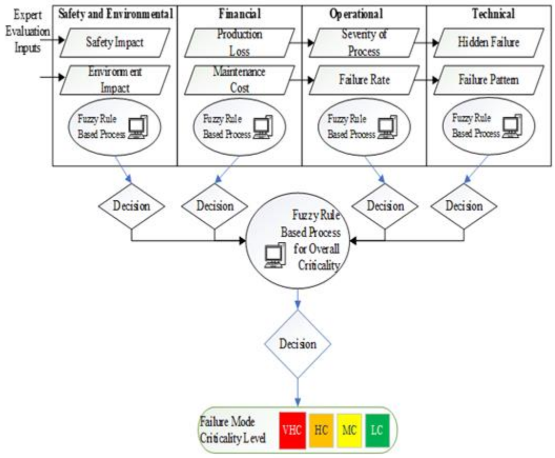

Fig. 2. Model with Selected Risk factor re-grouped into four main strategic perspectives adopted from Kermani [56] and Labib [57]

The first stage of the model demonstrates how the criticality of equipment could be determined in terms of each group of risk factors where the effectiveness of fuzzy logic has been presented. To understand how Fuzzy applied to such a decision-making problem, the three steps of defining the problem for fuzzy logic will be set out next. To create any decision problem, there are three steps that must be defined in the fuzzy logic MATLAB toolbox, Fuzzification, Rule evaluation and Defuzzification. Investigating equipment criticality with respect to safety and environmental consequences is crucial due to past catastrophic incidents. Two key inputs, safety and environmental impact, are used in the decision-making framework. Table 2 shows the linguistic values converted to fuzzy crisp values for safety and environmental impact levels using Likert's scale: Low (L), Medium (M), and High (H).

Table 2. Safety and Environmental Perspective - Fuzzy linguistic scale, Rules and Criticality Matrix

RULES/MATRIX	Fuzzy Parameter	(8,9,10)	(4,5,6,7)	(0,2,3)
Fuzzy Parameter	Safety Impact / Env. Impact	Deadly Hazardous (H)	Hazardous (M)	Slightly Hazardous (L)
(8,9,10)	Major Pollution (H)	Very High Critical	Very High Critical	High Critical
(4,5,6,7)	Significant Pollution (M)	Very High Critical	High Critical	Medium Critical
(0,2,3)	Minor Pollution (L)	High Critical	Medium Critical	Low Critical

Learning from failures involves examining the failure pattern and detectability type of each equipment failure. Therefore, the two main criteria for investigating valve failure detectability type are the failure pattern and detectability level. Table 3 describes the fuzzification of failure detectability type factors based on linguistic values for each factor and the matrix based on both input of technical perspectives. The detectability level divides into two levels, either it is hidden, or it is evident failure. For failure pattern input, known pattern considered as low level of criticality and unknown wear out classified as high critical. For a valve failure, if the associated detectability is hidden and it has an unknown failure then its criticality will be classified as very high. In contrast, if the associated failure of valve is due to known failure pattern and it is evident failure to operator then its criticality will be very low.

Table 3. Technical Perspective - Fuzzy linguistic scale, Rules and Criticality Matrix

RULES/MATRIX	Fuzzy Parameter	(6,7,10)	(0,2,4,5)
Fuzzy Parameter	Failure Type / Failure Pattern	Hidden (H)	Evident (L)
(8,9,10)	Unknown Pattern (H)	Very High Critical	Medium Critical
(4,5,6,7)	Random Failure (M)	High Critical	Low Critical
(0,2,3)	Known Pattern (L)	Medium Critical	Low Critical

Table 4. Operational Perspective - Fuzzy linguistic scale, Rules and Criticality Matrix

RULES/MATRIX	Fuzzy Parameter	(8,9,10)	(4,5,6,7)	(0,2,3)
Fuzzy Parameter	Severity of Process / Failure Rate	More than one severe service condition (H)	At least one severe service condition (M)	Normal Service (L)
(8,9,10)	Repeated failures (H)	Very High Critical	High Critical	Medium Critical
(4,5,6,7)	Occasional failures (M)	High Critical	High Critical	Medium Critical
(0,2,3)	Relatively few failures (L)	Medium Critical	Medium Critical	Low Critical

Failures are classified into three crisp sets: Low (L) for few failures, Medium (M) for occasional failures, and High (H) for repeated failures. The fuzzy sets with failure rate rankings and membership functions are shown in Table 4. Inline process control equipment like valves and sensors are exposed to process fluids, and in oil and gas plants, various conditions can damage these components. For instance, valves used in high-pressure drop services may fail sooner due to erosion and cavitation, increasing the probability of failure even with normal reliability data and process conditions. Process conditions are detailed in equipment datasheets, specifying environments such as corrosive service, contaminated fluids, or high temperatures, which can raise the failure rate. Input parameters for severe process conditions are determined by whether the valve operates in normal service, one severe service condition, or multiple severe service conditions.

Financial risk factors in maintenance management include production cost, maintenance cost, spare part cost, and production loss cost. The critical components are identified by focusing on production loss cost and maintenance cost, which are key inputs in fuzzy logic for financial factors. Production loss is referred to expected shutdown length, while maintenance cost of replacement parts or service costs, which are difficult to estimate numerically. Table 5 shows values for production cost loss, and values for maintenance cost.

Table 5. Financial Perspective - Fuzzy linguistic scale, Rules and Criticality Matrix

RULES/MATRIX	Fuzzy Parameter	(8,9,10)	(4,5,6,7)	(0,2,3)
Fuzzy Parameter	Production Loss / Maintenance Cost	Prolonged Production downtime (H)	Major Production downtime (M)	Acceptable Production downtime (L)

(8,9,10)	High Cost (H)	Very High Critical	High Critical	Medium Critical
(4,5,6,7)	Medium Cost (M)	High Critical	High Critical	Medium Critical
(0,2,3)	Low Cost (L)	Medium Critical	Medium Critical	Low Critical

The overall fuzzy logic approach is employed to impartially consider all factors in determining the equipment's criticality. While some inputs rely on subjective judgments, introducing uncertainty within each factor and between the four group dimensions, the concept of fuzzy logic is applied to address these uncertainties and interdependencies. The first phase of fuzzy logic involves merging the results from the de-fuzzification of the four criticality factors, and this outcome serves as an input to the model. Initially, there are four inputs, each representing the fuzzy logic outputs of a factor with four membership functions defined, resulting in a total of 250 rules. However, the increasing number of rules, coupled with subjective decision-making, can compromise result accuracy, and introduce uncertainty. To mitigate these concerns, a decision was made to reduce the number of rules. For instance, if three of the inputs are Very High Critical (VHC), then the output will be VHC, regardless of the fourth input.

Figure 3 provides the detailed rules for this reduction. The following categories were proposed to guide the creation of rules: Very High Critical (VHC), High Critical (HC), Medium Critical (MC), and Low Critical (LC). These rules establish a methodology for decision makers to generate rules efficiently. As illustrated in Figure 3, this category 1 to 4 of rules represents different scenario which explain in rule 1 to rule 11. These rules can be change in case operators or maintenance manager required to increase or decrease certain factors weight, for example, in case safety factors will be consider as highest priority compared to the other three factors, hence, the rules for category 1 (VHC) can be changed to reflect the important for safety factors.

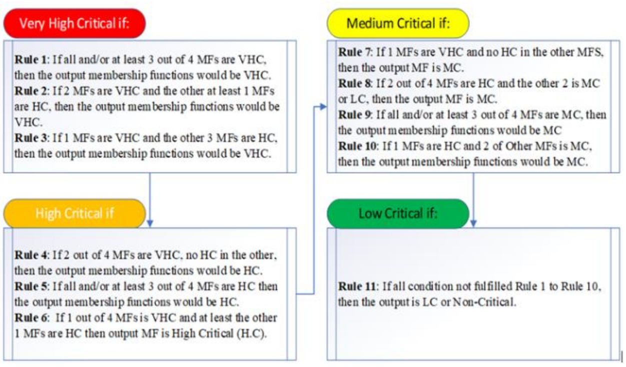

Fig. 3. Defined Rules for Overall Criticality Output

4. Case Study: FCC Catalyst Slide Valve FMECA

This case study referred to certain information gathered from CSB report of ExxonMobil Torrance Refinery explosion in 2015 which was published in 2017. The Torrance Refinery explosion in California is due to Spent Catalyst Slide Valve (SCSV) failure [38]. The main reason of the failure was the SCSV valve that was badly eroded but continue to operate. The root cause of the valve failure was pinpoint to the lack on maintenance strategy ExxonMobil had been operating the SCSV since January 2009 over six years and had not performed any inspection after the 4 to 5 year run length. ExxonMobil therefore operated the SCSV without verifying that the valve could perform its safety-critical function. As a result, on the day of the incident, the eroded SCSV could not establish a catalyst safeguard and did not prevent hydrocarbons from entering the air side of the FCC unit.

The fluid catalytic cracking (FCC) process converts heavy gas oils into higher valued lighter products, by cracking in the presence of the catalyst, under appropriate conditions of time, temperature, and pressure. The use of a catalyst promotes the cracking reaction at a lower temperature and pressure and yields products with more valuable properties than is possible with thermal cracking processes. Slide valve are control valves typically found on the FCCU include the regenerated catalyst slide valve (RCSV) and spent catalyst slide valve (SCSV). The primary valves are the regen and spent slide valves. The regen regulates the flow of regenerated catalyst to the riser, maintains the pressure head in the standpipe and protects the regenerator from a flow reversal. The spent controls the stripper catalyst level, regulates flow of spent catalyst to the regenerator and protects the reactor and main fractionator from a flow reversal [58].

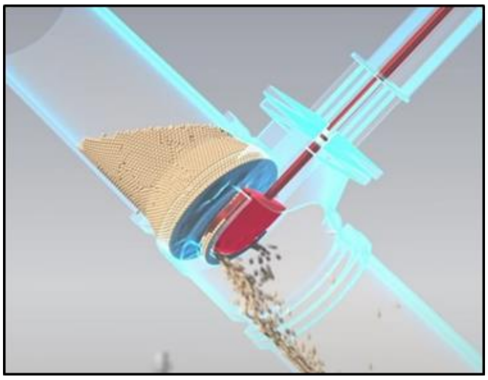

Fig. 4. Graphic showing how the catalyst slide valve controlling the catalyst level as shown in CSB report [38].

The Catalyst Slide Valve ensures that the catalyst is efficiently and effectively transferred to the regenerator. The Catalyst Slide Valve is subjected to harsh operating conditions, including high temperatures, abrasive catalyst particles, and corrosive gases. Therefore, the valve must be designed to withstand these conditions and provide reliable performance. Regular maintenance and inspection of the

Catalyst Slide Valve is crucial to ensure its proper functioning and prevent costly downtime [58].

4.1. SCSV Valve Function and Operation

Slide valves are control valves and are identified by their location and function in the FCC process Unit. Valves typically found on the FCCU include the regenerated catalyst slide valve, spent catalyst slide valve, cooled catalyst slide valve and the recirculation catalyst slide valve. The primary valves are the regen and spent slide valves. The regen regulates the flow of regenerated catalyst to the riser, maintains the pressure head in the standpipe and protects the regenerator from a flow reversal. The spent controls the stripper catalyst level, regulates flow of spent catalyst to the regenerator and protects the reactor and main fractionator from a flow reversal. The SCSV slide valve is a key piece of equipment that controls the ratio of catalyst to oil and reaction temperature in FCC units [58].

Slide valve is a valve which incorporates the sliding mechanism for the purpose to control the flowing fluid through the valve. The sliders of the valve move in rectilinear path to block and unblock the inlet or outlet port. The slide valve operates by the help of slide valve actuator to control the opening and closing of the valve. SCSV slide valve however is a slightly different compared to normal slide valve where it was designed to suit the spent catalyst control in FCC unit [38].

4.2. SCSV Valve Components

The term "slide valve" comes from Sliding Gate Valves. Slide gate valves are normally not used in general refinery services for control. However, in the case of slide valves for FCCU, the slide gate valve is utilized and functions well to control high temperature erosive service applications on the regenerated, spent, catalyst cooler, flue gas, regen catalyst and catalyst withdrawal valves [59].

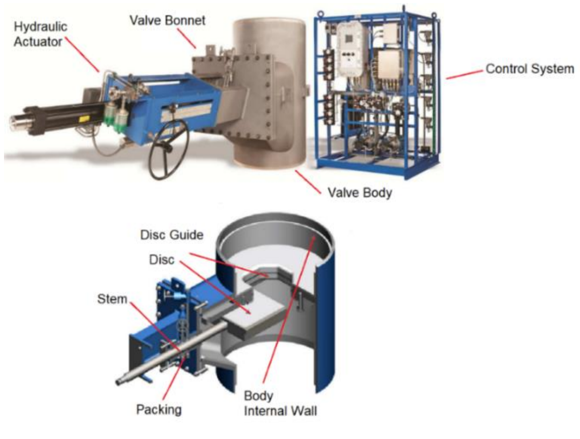

Fig. 5. Sample of Slide Valve main components (Image from IMI Valve Catalogue. This is not the actual valve manufacturer of failed SCSV in Torrance Refinery)

As shown in Figure 5, the primary components in a slide valve for FCC Spent catalyst consist of a body, bonnet, disc, disc guide, stem, actuator. The body is located in between two pipe flanges. The metal disc is mounted on stem that connected to disc to control sliding up and down to the seat. The flow of fluid is controlled by the disc as it passes through the circular piping. A packing component is situated in between the valve body and the stem to prevent any leakage occurring as the flow moves through the sliding line. The disc acts as a buffer between the metal disc and body as avoid any leakage as the valve is in the fully closed position [60].

4.3. SCSV Valve Functional Failure

The direction of catalyst flow must always be from the regenerator to the reactor and from the reactor back to the regenerator. A negative differential pressure across the regenerated catalyst slide valve can allow hydrocarbons to back-flow into the regenerator. This is called a flow reversal and can result in an uncontrolled afterburn and possible equipment damage. A negative pressure differential across the spent catalyst slide valve can allow air to back-flow from the regenerator into the reactor with equally disastrous consequences. To protect the reactor and the regenerator against a flow reversal, pressure differential controllers are used to monitor and control the differential pressures across the slide valves. If the differential pressure falls below a minimum set-point, the control system overrides the process controller and closes the valve. Only after the control system is satisfied will the control of the slide valve return to the process [38].

Normally the main critical components which considered are body, bonnet, sliding disc, stem, disc guide, packing actuator, control system. To identify SCSV valve failures, together with their causes and effect, and the current action taken to troubleshoot the failures, all information were gathered based on the report by Natalini [60] of the FCC SCSV failed valve components, supported by report from CSB [38] which briefly investigate the failure of the SCSV that cause the Torrance Refinery explosion.

4.4. SCSV Valve Failure Mode and Effect Analysis

The failure modes (FM) under consideration are drawn from a comprehensive evaluation of valve failure modes considering each of the key components and the corresponding possible causes of their failures. In industry, there are standards and guidelines for FMECA such as IEC60812 [61] for general guidelines. In the endeavour to uncover the failures of the SCSV, a thorough examination of numerous components is conducted to identify their failure modes along with their causes and subsequent effects. Each component's failure modes and their impacts on the broader system are meticulously documented within a specific FMECA form. Figure 6, illustrating the fault tree for fire/explosion in the regenerator of the FCC unit by Thangamani, et al. [62], underscores the potential severity of SCSV failure, which can lead to an FCC explosion. Additionally, Table 6 presents a succinct summary of common valve failure modes and potential root causes, drawing upon the recommended FMECA practices outlined in ISO14224 [63] and the FMECA study conducted on FCC units by Rooney, et al. [64].

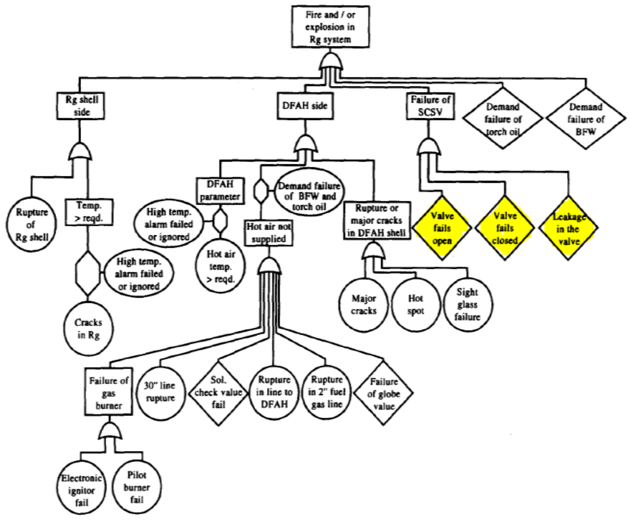

Fig. 6. The fault tree for the fire/explosion in the regenerator of FCC unit by Thangamani, et al. [62] highlight that failure SCSV may result FCC explosion.

Table 6. Summary of valve common failure mode and possible root cause based on recommended FMECA practice by ISO14224 [63] and FCC unit FMECA study by Rooney, et al. [64].

Common Failure Modes	Failure Effect	Related Component Failure
FM1: Internal Leakage/Passing - fluid passing through a valve when the valve is in its fully closed position.	Fluid (Hydrocarbon Gas/Liquid, Catalyst) pass through	Slide Stem Disc - erosion/cavitation, or due to obstruction, debris, or contaminants. Actuator failure, spring, hydraulic or mechanical failure.
FM2: Valve Failed Open/Close – Valve stop working and go to Close or Open position.	Affect catalyst movement	Slide Disc/Stem stuck due to debris, contaminants. Actuator failure, spring, hydraulic or mechanical failure. Control System or Hydraulic control Failure
FM3: Valve Body Damaged or Leaked – Process fluid leaked out from body	Fluid (Hydrocarbon Gas/Liquid, Catalyst) release to environment	Valve Body - Corrosion, Erosion or cavitation, material defect or mechanical fatigue or external corrosion

4.4.1. Experts Evaluation Input

To comprehensively explore diverse perspectives on each risk criteria, five experts were engaged in structured interviews. The primary objective was to gain a nuanced understanding of the subject matter through the thoughtful evaluation of each expert's insights. The selection of experts for this analysis is based on their involvement in current refinery operations, specifically in reliability studies and maintenance strategy work. The experts include Industrial Expert 1, who has over 10 years of experience in technical safety and has worked across various departments since the beginning of the plant operation. Industrial Expert 2, an operation supervisor with almost 25 years in the same company, is focused on daily operations and production. Industrial Expert 3, a maintenance reliability expert with about 15 years in the oil and gas industry, ensures reliability management and performance. Industrial Expert 4, a maintenance coordinator for instrument and control equipment, has over 12 years of maintenance execution experience in the same refinery but different units. Finally, Industrial Expert 5, a senior instrument engineer with 12 years of experience in oil and gas downstream, provides technical expertise in valve engineering.

The survey questionnaire was meticulously crafted using the Likert Scale. This method, with reference to Fuzzy crisp for each group of perspectives, employs a scale ranging from 0 to 10. The design of this scale aligns seamlessly with the fuzzy crisp concept elucidated in the same chapter, providing a structured framework for expert evaluation. The scale embedded within the questionnaire serves as a crucial tool for capturing the richness and nuances of expert opinions. The range from 0 to 10 allows for a broad spectrum of responses, reflecting the depth and diversity of expert perspectives. Each point on the scale corresponds to a specific gradation within the fuzzy crisp framework, ensuring a systematic and comprehensive assessment. The questionnaire is thoughtfully structured to address each risk perspective of the criticality analysis, prompting experts to articulate their evaluations across the defined scale. Table 7 below represents the scale and the relationship between the fuzzy crisp for all the eight risk factors.

Table 7 Questionnaire scale for the experts FMECA risk perspectives input for all eight risk factors with relationship with fuzzy crips.

Questionaire Scale	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Fuzzy Parameters	**(0,2,3)**				**(4,5,6)**				**(7,8,10)**		
Fuzzy Crisps Level	**Low**				**Medium**				**High**		
Impact on Safety	Slightly Hazardous				Hazardous				Deadly Hazardous		
Impact on Environment	Minor Pollution				Significant Pollution				Major Pollution		
Serverirty of Process Condition	Normal Service				At least one severe service condition				More than one severe service condition		
Failure Rate	Relatively few failures				Occasional failures				Repeated failures		
Production Loss	Acceptable downtime				Major downtime				Prolonged downtime		
Maintenance Cost	Low Cost				Medium Cost				High Cost		
Failure Pattern	Known Pattern				Random Failure				Unknown Pattern		
Fuzzy Parameters	**(0,2,4,5)**						**(6,7,10)**				
Fuzzy Crisps Level	Low						High				
Failure detectability	Evident						Hidden				

4.4.2. Safety Perspective Expert Input Result

For both safety and environment risk factor input, experts were asked to assess the risk factors on a scale of 1 (least critical) to 10 (most critical) in terms of the possible impact for each failure mode (FM1 to FM3) in the survey. This evaluation aligns with the Fuzzy scale, for Safety and Environmental Fuzzy crisp. The survey results are organized and presented in Table 8 and 9. The survey results reveal insights into safety and environmental risk inputs for various failure modes related to valves. In terms of safety risk, experts rated FM1 with a mean score of 8.8, signalling a critical safety hazard, followed by FM2 at 6.8, indicating significant risk, and FM3 at 7.4, denoting a substantial safety hazard. On the environmental front, FM1 was rated at 5.6, suggesting a significant environmental hazard, while FM2 scored 4.4, indicating a moderate environmental risk. Conversely, FM3 received a rating of 5.2 on average, implying a medium environmental hazard.

Table 8 Safety Impact and environmental impact inputs for each failure mode

Failure Modes (Impact on Safety)	**Exp1**	**Exp2**	**Exp3**	**Exp 4**	**Exp5**	**Mean**
FM1: Internal Leakage/Passing	8	9	9	9	9	8.8
FM2: Valve Failed Open/Close	7	6	7	6	8	6.8
FM3: Valve Body Damaged or Leaked	8	8	8	6	7	7.4

Table 9 Environmental impact inputs for each failure mode

Failure Modes (Impact on Environment)	**Exp1**	**Exp2**	**Exp3**	**Exp 4**	**Exp5**	**Mean**
FM1: Internal Leakage/Passing	6	7	7	3	4	5.6
FM2: Valve Failed Open/Close	5	6	5	2	4	4.4
FM3: Valve Body Damaged or Leaked	7	6	7	2	4	5.2

The evaluation underscores the criticality of internal leakage as the most significant safety risk due to its potential for uncontrolled releases, while damage to valve bodies poses substantial environmental risks. These findings emphasize the need for proactive measures to mitigate safety and environmental hazards associated with valve failures in industrial settings.

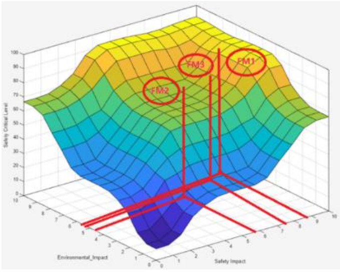

Fig 7. The result of Fuzzy rule inference for each failure modes mode with regards to safety and environment perspectives criticality level.

Figure 7 shows the fuzzy criticality assessment conducted based on safety and environmental perspectives, incorporating expert survey inputs, reveals a comprehensive understanding of the criticality levels associated with various failure modes related to valves in the oil and gas industry. From the safety perspective, FM 1 is identified as Very High Critical with a score of 91.3, indicating significant safety hazards associated with internal leakage/passing. FM2 with a score of 68.8, denoting a High Critical level due to valve failure in the open/close position. FM3 also exhibits a High Critical level with a score of 72.4, attributed to valve body damage leading to fluid leakage. These assessments underscore the paramount importance of addressing safety risks within the industry, especially concerning valve failures, which could potentially lead to severe consequences for personnel safety and environmental integrity.

4.4.3. Financial Perspective Expert Input Result

There are two financial dimensions that need to be considered as inputs to FMECA analysis, for example the cost of maintenance per year and the production cost loss in the case of failure. One could argue that there are many essential elements associated with financial concern such as the potential cost loss of environmental damages, losing reputation of company and many others. For financial perspectives input, experts were asked to assess the risk factors on a scale of 1 to 10 in term of the possible financial impact for each failure mode (FM1 to FM3) in the survey. This evaluation aligns with the Fuzzy scale introduced in previous section, for Financial Fuzzy crisp. The survey results are organized and presented in Table 10 and 11.

In evaluating production loss (downtime) input, FM1 received a high score of 9.2, indicating an extremely high risk of production loss due to prolonged downtime. FM2 garnered a moderate score of 5.0, suggesting a moderate risk of production loss compared to internal leakage. FM3 was rated at 9.0, highlighting an equally high risk of production loss akin to internal leakage. For maintenance cost input, FM1 was rated at 7.8, suggesting a moderate to high maintenance cost. FM2 received a relatively lower rating of 3.0, indicating a lower perceived maintenance cost compared to FM3, which received a rating of 8.0, signifying a higher maintenance cost due to the complexity of repair or replacement procedures.

Table 10 Production loss inputs for each failure mode

Failure Modes (Production Loss)	**Ex p1**	**Ex p2**	**Ex p3**	**Ex p 4**	**Ex p5**	**Mean**
FM1: Internal Leakage/Passin g	10	9	10	10	7	9.2
FM2: Valve Failed Open/Close	4	5	4	7	5	5.0
FM3: Valve Body Damaged or Leaked	9	9	10	10	7	9.0

Table 11 Maintenance Cost input for each failure mode

Failure Modes (Maintenance Cost)	**Ex p1**	**Ex p2**	**Ex p3**	**Ex p 4**	**Ex p5**	**Mean**
FM1: Internal Leakage/Passin g	8	7	8	9	6	7.8
FM2: Valve Failed Open/Close	2	2	3	4	4	3.0
FM3: Valve Body Damaged or Leaked	9	8	9	7	7	8.0

In summary, internal leakage/passing and damage to valve bodies were identified as posing the highest risks in terms of production loss, aligning with their critical nature and potential for extended downtime. Valve failure in open/close positions, while significant, posed a moderate risk of production loss compared to the other failure modes. Similarly, the evaluation highlighted the high maintenance costs associated with addressing internal leakage and damage to valve bodies, underscoring the importance of proactive maintenance strategies to minimize downtime and optimize operational efficiency.

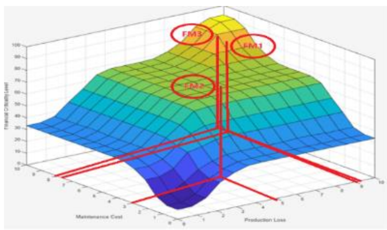

Fig 8. The result of Fuzzy rule inference for each failure modes with regards to financial perspectives criticality level

Based on the fuzzy criticality assessment result as depicted in Figure 8, conducted from the financial perspective, the evaluation indicates significant insights into the criticality levels of various failure modes related to valves. The assessment, which incorporates inputs from five experts, reveals that FM1 exhibits a very high criticality level with a score of 75.8, indicating substantial concern regarding its impact on production loss and maintenance cost. FM3 also emerges as highly critical with a score of 77.9, underscoring the potential financial risks associated with process fluid leakage from valve body damage. These findings suggest that both FM1 and FM3 pose considerable threats to operational efficiency and financial stability due to their adverse effects on production downtime and maintenance expenses. In contrast, FM2, while still significant, is rated at a medium criticality level with a score of 56, indicating a comparatively lower but still notable impact on operational and financial aspects.

4.4.4. Operational Perspective FMECA Result

For operational perspectives input, experts were asked to assess the risk factors on a scale of 1 to 10 in term of the possible financial impact for each failure mode (FM1 to FM3) in the survey. The survey results are organized and presented in Table 12 and 13.

Table 12 Severity of process inputs for each failure mode

Failure Modes (Severe Process Condition)	**Exp 1**	**Exp 2**	**Exp 3**	**Ex p 4**	**Exp 5**	**Mea n**
FM1: Internal Leakage/Pass ing	9	10	9	5	8	8.2
FM2: Valve Failed Open/Close	5	4	3	2	4	3.6
FM3: Valve Body Damaged or Leaked	7	8	8	5	7	7

Table 13 Failure rate inputs for each failure mode

Failure Modes (Failure Rate)	**Exp 1**	**Exp 2**	**Exp 3**	**Ex p 4**	**Exp 5**	**Mea n**
FM1: Internal Leakage/Pass ing	7	6	7	6	7	6.6
FM2: Valve Failed Open/Close	7	7	6	7	5	6.4
FM3: Valve Body Damaged or Leaked	2	3	4	5	5	3.8

The evaluation of severity of process conditions and failure rates among different valve failure modes provides valuable insights into operational risks for the SCSV. Internal leakage/passing (FM1) emerges as the most severe concern, with experts rating it at 8.2, signifying potential operational disruptions and safety hazards. In contrast, FM2 received a lower severity rating of 3.6, indicating a comparatively lesser impact on process conditions. FM3 was rated at 7.0, highlighting significant risks associated with fluid leakage. For failure rates, FM1 and FM2 received moderate to high ratings of 6.6 and 6.4, respectively, suggesting a higher likelihood and operational interruptions. Conversely, FM3 rated lower at 3.8, indicating a relatively lower frequency of occurrence.

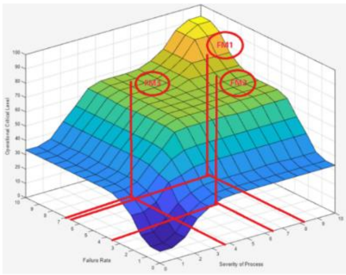

Fig 9. The result of Fuzzy rule inference for each failure modes with regards to operational perspectives criticality level

Based on the fuzzy criticality assessment conducted from the operational perspective as shown in Figure 9, the evaluation provides insights into the criticality levels of various failure modes associated with valves. The assessment, based on inputs from five experts, reveals that FM1 exhibits a high criticality level with a score of 70.2, indicating significant concerns regarding the severity of process conditions and failure rates impacting internal leakage or passing of fluid through valves. FM3 also emerges as highly critical with a score of 66.7, emphasizing the potential risks associated with valve body damage and fluid leakage. Both failure modes highlight the importance of considering the operational environment and failure rates in assessing criticality levels. In contrast, FM2 is rated at a medium criticality level with a score of 64.3, suggesting a moderate impact on operational efficiency and reliability.

4.4.5. Technical Perspective FMECA Result

From the [38] incident report , it shows that the SCSV had severely eroded over six years of operation and was unable to seal internally and leaked without any sign to alarm the operator. From the causal analysis of the explosion, erosion damage of the SCSV had developed over six years of operation likely compromised the SCSV, and it could not maintain a catalyst barrier while the FCC unit was in Safe Park [38]. Hence, the dominant failure pattern for the SCSV is the wear out or the internal stem and this is not detectable without opening the valve itself. The survey results are organized and presented in Table 14 and 15 below.

Table 14 Detectability Type Failure inputs for each failure mode

Failure Modes (Failure detectability)	**Ex p1**	**Ex p2**	**Ex p3**	**Ex p 4**	**Ex p5**	**Mean**
FM1: Internal Leakage/Passing	8	8	9	9	8	8.4
FM2: Valve Failed Open/Close	3	4	5	2	4	3.6
FM3: Valve Body Damaged or Leaked	4	5	5	3	4	4.2

Table 15 Failure pattern inputs for each failure mode

Failure Modes (Failure Pattern)	**Ex p1**	**Ex p2**	**Ex p3**	**Ex p 4**	**Ex p5**	**Mean**
FM1: Internal Leakage/Passing	3	4	4	4	2	3.4
FM2: Valve Failed Open/Close	6	7	6	7	9	7.0
FM3: Valve Body Damaged or Leaked	4	4	3	5	3	3.8

In evaluating detectability and patterns related to valves, experts have provided insightful ratings indicating the potential risks associated with hidden and evident failures. FM1 received a notable rating of 8.4, indicating a high level of hidden risk, posing significant operational and safety concerns due to its undetectable nature when fluid passes through a valve in its fully closed position. Conversely, FM2 garnered a rating of 3.6, suggesting a lower level of hidden risk, implying that such failures may be more evident or detectable compared to internal leakage. The rating for FM3 stands at 4.2, reflecting a moderate level of hidden risk, despite fluid leakage being less concealed than internal leakage, it still poses operational challenges and safety risks.

In terms of failure patterns, FM1 scored 3.4, indicating a known failure pattern, allowing for proactive maintenance measures. FM2 received a higher rating of 7.0, reflecting a higher level of uncertainty in its failure pattern, making it challenging to predict and address such failures. Rated at 3.8, FM3 shows a known failure pattern associated with process fluid leakage, posing challenges in maintenance planning and risk mitigation despite the pattern being known. The results emphasize the critical importance of proactive monitoring and maintenance of valves, particularly for those crucial for process safety like the SCSV. They also highlight the need for comprehensive valve maintenance programs, including regular inspections and condition monitoring, to mitigate the risks associated with hidden failures and unpredictable patterns, ensuring operational reliability and safety within the refinery's processes.

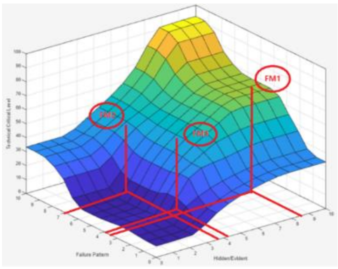

Fig 10. The result of Fuzzy rule inference for each failure modes with regards to technical perspectives criticality level

Figure 10 presents the fuzzy criticality assessment resulted from the technical perspective assessment; the evaluation offers insights into the criticality levels of various failure modes associated with valves. The assessment, based on inputs from five experts, indicates that FM1 exhibits a medium criticality level with a score of 61.3. This suggests notable concerns regarding the detectability of failure detectability types and the patterns associated with internal leakage or passing of fluid through valves. FM2 and FM3 are rated at low criticality levels, with scores of 38.4 and 40.1 respectively. These scores reflect a lower level of concern regarding failure patterns and detectability for these modes compared to FM1.

The comprehensive fuzzy criticality assessment highlights the importance of considering technical factors such as failure detectability type and pattern in assessing the criticality of equipment components. While Failure Mode 1 indicates a moderate level of criticality, FM2 and FM3 suggest relatively lower risks in terms of technical considerations. By leveraging fuzzy logic methodologies and expert inputs, the assessment provides valuable insights for prioritizing maintenance efforts, improving failure detection mechanisms, and optimizing asset management practices to enhance system reliability and minimize operational risks in industrial environments. The findings underscore the significance of integrating technical perspectives into decision-making processes to ensure the effective management and maintenance of critical systems and components.

4.4.6. Overall FMECA Criticality

The overall criticality, detailing the SCSV FMECA summary of input results from experts and criticality levels for each perspective using fuzzy crisp and overall Fuzzy rules, is provided in Table 16.

Table 16 Each perspective criticality level result for each failure mode

Overall Criticality Level					
Failure Modes	Safety	Financial	Operation	Technical	Overall Criticality
FM1: Internal Leakage/Passing	91.3 VHC	75.8 VHC	70.2 HC	61.3 MC	**89.7 VHC (Rule 2)**
FM2: Valve Failed Open/Close	68.8 HC	56 MC	64.3 MC	38.4 LC	**61.3 MC (Rule 10)**
FM3: Valve Body Damaged or Leaked	72.4 HC	77.9 VHC	66.7 HC	40.1 LC	**66.7 HC (Rule 6)**

Table 17 Overall Criticality Level

Failure Modes	**Safety Perspectives**			**Financial Perspectives**		
	Safety	Env.	Criticality	Prod Loss	Main. Cost	Criticality
FM1: Internal Leakage/Passing	**8.8**	**5.6**	91.3 VHC	**9.2**	**7.8**	75.8 VHC
FM2: Valve Failed Open/Close	**6.8**	**4.4**	68.8 HC	**5**	**3**	56 MC
FM3: Valve Body Damaged or Leaked	**7.4**	**5.2**	72.4 HC	**9**	**8**	77.9 VHC
Failure Modes	**Operational Perspectives**			**Technical Perspectives**		
	Failure Rate	Severity of Process	Criticality	Evi Hidden/ dent	Failure Pattern	Criticality
FM1: Internal Leakage/Passing	**6.6**	**8.2**	70.2 HC	**8.4**	**3.4**	61.3 MC
FM2: Valve Failed Open/Close	**6.4**	**3.6**	64.3	**3.6**	**7**	38.4

			MC			LC
FM3: Valve Body Damaged or Leaked	**3.8**	**7**	66.7 HC	**4.2**	**3.8**	40.1 LC

The results of the fuzzy logic-based criticality assessment for the three failure modes reveal varying degrees of criticality across diverse perspectives. In FM1, overall criticality levels are rated as Very High Critical which resulting from VHC-VHC-HC-MC across safety, financial, operational and technical perspectives resulting 89.9 in Criticality Number. For FM2 -Valve Failed Open/Close exhibits final score as Medium Critical with 61.3 criticality number. The FM2 got HC-MC-MC-LC across safety, financial, operational and technical perspectives. While for FM3 -Valve Body Damaged or Leaked, receives High Critical overall criticality ratings with slightly passing border criticality number of 66.7. Overall, the results suggest that FM1 are the most critical failure modes, then follow with FM3, and FM2 being of medium criticality. Based on the result, the fuzzy logic-based FMECA approach suggests that the method allowed for a more comprehensive and nuanced assessment of criticality, considering multiple perspectives and factors. This can help prioritize maintenance and mitigation efforts, as well as inform decision-making around resource allocation and risk management. Additionally, the use of fuzzy logic-based FMECA approach can also provide a more reliable assessment of criticality compared to traditional FMECA RPN methods.

4.4.6.1. Comparison with Traditional RPN analysis

The RPN (Risk Priority Number) analysis is a widely used method for assessing the risk associated with failure modes in a system. It involves assigning scores to three factors - Occurrence, Severity, and Detectability - and multiplying them to obtain a criticality number (RPN). In the method described in the given table, the traditional RPN analysis is used to compare the results of the fuzzy logic-based criticality assessment. To ensure consistency, the same scale of 1 to 10 is used for each factor - Occurrence, Severity, and Detectability - in both methods. The severity input taken from safety impact factors experts input mean, while the occurrence input was based on failure rate input factors, and the detectability input was determined from the failure detectability type input factors provided in the expert surveys. Table 18 shows the mean values obtained from experts for each factor, as well as the RPN number calculated by multiplying the three factors.

The traditional RPN analysis and the fuzzy logic-based criticality assessment provide different perspectives on the criticality of the failure modes. Comparing the results of the two approaches, it is evident that there are some similarities and differences. For instance, FM1 is rated as Medium Critical in the RPN analysis, while it is rated as Very High Critical in the fuzzy logic-based criticality assessment. This difference can be attributed to the fact that the fuzzy logic-based assessment, by considers more factors and perspectives, it also provides more nuanced and accurate determination in considering each factor. Similarly, FM2 and FM3 is rated as Low Critical in the traditional RPN analysis, while it is rated as Medium Critical and High Critical respectively in the fuzzy logic-based criticality assessment. This difference can be attributed to the fact that the fuzzy logic-based assessment considers more perspectives and risk factors while the RPN analysis only consider the three factors. Furthermore, as discussed in literature review, this is the evidence of the weakness of traditional RPN where all the three factors multiply to each other to get the overall RPN number, which not represent the relative importance of each factor.

Table 18 Traditional RPN Analysis using the same input for comparison

Failure Modes	Failure Rate as Occurrence (O)	Safety as Severity (S)	Hidden Failure Scale as Detectability (D)	**RPN Number O x S x D (max 1000)**
FM1: Internal Leakage/Passing	6.6	8.8	8.4	**510** (Medium Critical)
FM2: Valve Failed Open/Close	6.4	6.8	3.6	**156** (Low Critical)
FM3: Valve Body Damaged or Leaked	3.8	7.4	4.2	**118** (Low Critical)

The inclusion of fuzzy rules and expert input allows for a more holistic and nuanced understanding of the potential impact of failure modes, considering both quantitative and qualitative factors. Furthermore, the results of the overall criticality assessment can also be used to inform the development of a risk management plan. By prioritizing the most critical failure modes, resources can be allocated more effectively to mitigate potential risks and minimize the impact of failures. This can ultimately lead to improved safety, reduced production losses, and lower maintenance costs. Overall, the fuzzy logic-based FMECA approach provides a valuable tool for organizations to assess and manage risks associated with potential failure modes. By considering multiple perspectives and factors, this approach can provide a more comprehensive and accurate assessment of criticality, allowing for more effective risk management and resource allocation.

5. Discussion and Conclusion

This study presents a unique and innovative approach to managing risk assessment of valve maintenance strategy in refineries. The findings highlight the shortcomings of the conventional FMECA technique, which frequently fails to recognize and take into consideration the uncertainties present in intricate risk analysis scenarios [15, 16]. Maintenance manager can now address the shortcomings of traditional FMECA, such as subjective descriptions and the relative importance of different risk classifications, thanks to the Fuzzy based FMECA methodology, which was developed to improve the accuracy and comprehensiveness of risk analysis by incorporating fuzzy logic principles [2, 17]

The strategic multi-perspective model utilized in this study incorporates fuzzy-logic rule-based criticality assessment, which enables decision-makers to make informed decisions about maintenance needs based on a comprehensive analysis of risk factors. By considering safety, technical, financial, and operational perspectives, the model provides a holistic view of maintenance risk factors when determining the criticality of failure modes. The results of this study demonstrate that the inclusion of additional perspectives and risk factors leads to more accurate criticality levels. The model's ability to identify failure modes that may not be critical in one perspective but highly critical in another is particularly noteworthy. This insight can help decision-makers prioritize maintenance tasks and allocate resources more effectively.

Moreover, the strategic multi-perspective model presented in this study has the potential to improve the overall efficiency and effectiveness of valve maintenance strategies in refineries. By providing a comprehensive analysis of maintenance risk factors, decision-makers can make informed decisions about maintenance needs, which can ultimately lead to increased safety, reduced downtime, and improved operational efficiency. In conclusion, this study introduces a novel approach to managing valve maintenance strategy in refineries. The strategic multi-perspective model, incorporating fuzzy-logic rule-based criticality assessment, provides decision-makers with a comprehensive analysis of maintenance risk factors from different perspectives. The results of this study demonstrate the potential of this approach to improve the overall efficiency and effectiveness of valve maintenance strategies in refineries.

6. Future Research

There are several areas where the model could be further improved to enhance its effectiveness. For instance, future work could extend the risk criteria standard FMECA to different applications or equipment, incorporating special risk criteria tailored to specific equipment. This would enable decision-makers to identify potential risks more accurately and take appropriate measures to mitigate them.Another area for improvement is exploring the strategic model of FMECA from different perspectives beyond the four groups presented in this research. This could provide a more comprehensive understanding of the equipment and its maintenance needs, allowing decision-makers to make more informed decisions. Additionally, incorporating more than two risk criteria for each group, this could provide a more nuanced understanding of the equipment's maintenance needs and help decision-makers prioritize maintenance tasks more effectively. However, by adding more factors, it would require complex Fuzzy logic rules tools which need to have more rules.

Finally, future research could explore the integration of advanced technologies such as Artificial Intelligence (AI) and Machine Learning (ML) element in the methodology to further optimize the model's performance. These technologies could help decision-makers identify potential risks more accurately. This would enable decision-makers to take proactive measures to prevent equipment failures and ensure the reliability of critical valves. Overall, these improvements could further enhance the effectiveness of the model and provide decision-makers with valuable insights to optimize equipment maintenance

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Author contributions

Faizal Abdullah: Conceptualization and Design, Data Collection, Analysis and Interpretation of Results, Draft Manuscript Preparation **Mohd Khairi Abu Husain:** Supervision, Reviewing, and Approval of Final Manuscript.

All authors reviewed the results and approved the final version of the manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

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