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INTEGRATED FMEA-HAZOP FRAMEWORKS FOR INDUSTRIAL HAZARD RISK ASSESSMENT: A THOROUGH REVIEW

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Abstract

The nature of industrial operations in the chemical processing, petrochemicals, manufacturing, energy production, pharmaceuticals and oil and gas sectors are getting more complex, automated and interdependent leading to increased safety and operational risks. Conventional risk testing methods, which include Failure Mode and Effects Analysis (FMEA), Hazard and Operability Study (HAZOP), are extensively used to recognise and eliminate possible failures. FMEA offers a semi-quantitative, systematic method of assessing failure modes and ranking risks based on Risk Priority Numbers (RPNs), whereas HAZOP is a qualitative and team-based means to identify process deviations and process vulnerabilities. Although they are generally used, each method has its internal constraints in their application as an isolated technique. This review is systematic in its approach to studying the integrated FMEAHAZOP frameworks, which combine the merits of the two approaches to provide it with a wholesome, dependable, and actionable risk analysis. The paper speaks about historical development, methodological background, major elements, strengths, and weaknesses of FMEA and HAZOP and then conceptually covers how they have been introspectively integrated, including qualitative and quantitative analysis, risk prioritization, and mitigation planning. The synthesis of existing literature reveals the benefits, difficulties, and industry-related implementation of integrated frameworks in the review that contributes to the improvement of industrial safety, operational security, and the future study of the hybrid methodologies of risk assessment.

Keywords: FMEA, HAZOP, Integrated Risk Assessment, Industrial Safety, Hazard Analysis, Risk Prioritization, Process Deviations, Hybrid Frameworks

Introduction

The industrial systems in the chemical processing industry, petrochemicals, manufacturing, energy generation, pharmaceuticals, and oil and gas industries are becoming characterized by the complex operations, high level of automation and tightly integrated processes. It is in this ever-increasing complexity that the possibility of the occurrence of hazardous events possibilities, whether due to equipment malfunctions and process variation, or due to systemic human-machine interactions has only increased greatly [1]. In an effort to ensure high levels of safety, reliability, and compliance with the established regulations, industries depend greatly on effective hazard identification and risk assessment strategies. Failure Mode and Effects Analysis (FMEA) and Hazard and Operability Study (HAZOP) are some of the most popular tools and form the basis to use as the foundational techniques. FMEA offers a systematic, bottom-up, semi-quantitative methodology that determines possible failure mechanisms, their causes, and their results and gives a prioritization in terms of Risk Priority Numbers (RPNs). Nevertheless, it is occasionally not deep enough to represent interactions among complex processes [2]. By contrast, the qualitative, guideword, and team-based analysis that HAZOP provides is good at identifying subtle operational deviations and systems vulnerabilities but tends to fail at quantifying the risk or giving any priority to deviations.

It is important to note that whereas the two approaches are not without their weaknesses, their limitations have led to the increasing use of integrated FMEA-HAZOP systems in industries as a way to attain a more holistic approach to industrial risks. As a result of such hybrid methods, the quantification potential of FMEA can be structured and yet the diagnostic depth and richness of HAZOP is available, thus being especially useful in complex operations that may have multi-dimensional risk factors and dynamic system behavior. The last several years witnessed the rise of diverse hybrid models, sequential integration approaches, digital solutions, and AI-based assessment tools that are supposed to simplify the process of integration and promote the quality of risk assessments[3]. Although this has been achieved, no cohesive knowledge has been attained on these integrated frameworks, their efficacy and their feasibility in the industry. It is in this context that the current review provides a thorough and methodical analysis of built-in FMEAHAZOP frameworks, critical analysis of the currently existing models, sector-specific implementations, methodological developments, and gaps in the research to enhance better risk evaluation and safer industrial procedures.

S. No.	Author(s)	Year	Title	Source / Publisher
1	Sotoodeh, A., Abdullah, M., Ahmed, T., & Chandrasekar, M. [4]	2024	Safety in Systems: A Comprehensive Literature Review of PHA, FMEA, HAZOP, and Fault Tree Analysis	IISE Annual Conference Proceedings, Institute of Industrial and Systems Engineers (IISE)
2	Nehal, N., Mekkakia-Mehdi, M., Lounis, Z., Guetarni, I. H., & Lounis, Z. [5]	2024	HAZOP, FMECA, monitoring algorithm, and Bayesian network integrated approach for an exhaustive risk assessment and real-time safety analysis: Case study	Process Safety Progress
3	Kozlov, K. V. [6]	2025	Risk Assessment Tools in Project and Quality Management: from Checklists to HAZOP: a Comparative Review of Qualitative Risk Assessment Methods	Components of Scientific and Technological Progress
4	Villa, V., Paltrinieri, N., Khan, F., & Cozzani, V. [7]	2016	A short overview of risk analysis background and recent developments	Dynamic Risk Analysis in the Chemical and Petroleum Industry
5	Kruzhilko, O., Maystrenko, V., Polukarov, O., Kalinchyk, V. P., Shulha, A., Vasyliev, A., & Kondratov, D. [8]	2020	Improvement of the approach to hazard identification and industrial risk management, taking into account the requirements of current legal and regulatory acts	Archives of Materials Science and Engineering

1. Background of Industrial Hazard Risk Assessment

Industrial hazard risk assessment can be defined as the methodical procedure of identifying, examining, and assessing the possible risks that can pose dangers to the safety, dependability, and survival of the industrial activity. The nature of industrial risks has become more complex with the evolution of industries throughout the world to be more automatic, interconnected, and high-performance production systems. The operation of modern facilities in large volumes of hazardous materials, high-level process control, and complex human machine relations makes them prone to failures that can lead to disastrous outcomes, like explosions, toxic releases, fire, equipment failures, environmental pollution and loss of life.

The main idea behind industrial hazard risk assessment is to anticipate the places where failures may occur and operational deviation may take place before it develops into a detrimental event. This entails the identification and analysis of hazard origins, their probability and potential effect to the workers, assets, environment and community. Risk assessment has since become an element of the industrial safety management over the years due to the stringent regulations, global safety standards, and increased expectations of the society to have a safer and sustainable industrial practice. The different analytical methods including the qualitative, such as HAZOP, to quantitative and semi-quantitative, such as FMEA, have been evolve to aid in making decisions that are structured and evidence-based.

As industrial complexities rise, the drawbacks of single standalone applications have been more evident. This has given rise to the concept of integrated and hybrid risk assessment frameworks which integrate the best attributes of various methodologies to give more accurate, comprehensive and actionable information. Since the development of the industries is progressing, the history and development of industrial hazard risk assessment sheds light on its significance in improving the safety of operation, better visibility of risks, and proper hazard avoidance measures.

2. Need for Systematic and Structured Risk Analysis Tools

The modern industrial setting is being filled with complexity, automation, and interdependence which makes possible risks more difficult to foresee and control [9]. The large variety of possible failure situations that can occur in such sophisticated systems is no longer well represented through traditional and informal approaches or experience-related methods, and the systematic and structured risk analysis tools are needed that provide transparent, systematic, and consistent methods of identifying and evaluating hazards. With these tools, industries can decompose the complex processes, analyze deviations and failure modes and quantitatively estimate the impacts of them without disregarding even low frequency but high impact risks. Structured methodologies enhance interdisciplinary communication and promote regulatory compliance, as well as give a solid base of audit, mitigation planning, and continuous improvement by encompassing standardized procedures and documentation practices. Moreover, FMEA, HAZOP, and integrated systems allow rankings risks in terms of quantitative or semi-quantitative scores so that the resources could be efficiently distributed to the most important problems. These tools are critical in ensuring the safety of industry, reducing operational setbacks and protecting the human life and the environment, and systematic risk analysis is the key to the safe and reliable operation of the modern industrial systems.

3. Overview of FMEA and HAZOP: Strengths and Limitations

Two common approaches to the development of an assessment of hazard risks in industries are Failure Mode and Effects Analysis (FMEA) and Hazard and Operability Study (HAZOP), both having their advantages and limitations. The FMEA is a bottom-up method that is systematic, semi-quantitative, identifying the possible failure modes, causes, and effects on the performance of a system, and capable of prioritizing risks using the Risk Priority Number (RPN). It is especially useful in the initial design and development phases because of its well-organized workflow and clarity. Nevertheless, FMEA can also be subjective because it does not always represent the intricate interactions and the multi-dimensional process deviations, and may be subject to the expert judgment. HAZOP, conversely, is a top-down, team-based, and qualitative methodology, which relies on guidewords to purposefully identify deviations in the processes, operational weak points, and the possible hazardous areas. Its interactive and diagnostics quality enables it to identify any latent risks that could not be easily identified by the use of numbers. However, HAZOP is time-consuming, resource intensive and lacks quantitative prioritization and results are very much influenced by the expertise of the facilitator and team experience. Knowledge of the relative merits and flaws of FMEA and HAZOP offers a basis to the integrated structures to combine the systematic approach of quantification with thorough qualitative assessment to improve the process of assessing the risk of hazards in industries.

Failure Mode and Effects Analysis (FMEA)

Failure Mode and Effect Analysis (FMEA) is a methodology that follows a sequence of steps that attempt to define the possible failure modes within a system, process, or product, the causes and effects of these failures, and risk prioritization in terms of severity, frequency, and observability. FMEA is used to enable the organization to concentrate on the most important problems, design reliability, process safety, and prevention measures by assigning a Risk Priority Number (RPN) to each possible failure. Its systematic and proactive nature enables its wide applicability in industries especially in the design, development and operational stages.

Strengths of FMEA

FMEA offers a bottom-up methodical method of identifying the possible failure modes, their causes, and their consequences to industrial systems. It is simple to implement in the design, development, and preliminary operations due to its structured format and stepwise process. The calculation of the Risk Priority Number (RPN) is one of the strengths of this because the identification risks may be semi-quantitatively prioritized. This assists decision-makers to allocate resources in a proper way to deal with the most critical modes of failure. FMEA also promotes cross-functional participation, aids in the documentation of vulnerabilities in the system and promotes lifecycle-long continuous improvements of industrial processes.

Limitations of FMEA

FMEA has a number of limitations even though it is useful. It is usually unsuccessful to represent non-uniform interactions among various components or subsystems, particularly within large operations in the industrial sector. The approach is very subjective and inconsistent in its approach to presenting severity, occurrence, and detection ratings as the process is based on the subjective judgment of the experts. FMEA is also likely to concentrate more on single-point failures as opposed to systemic or dynamic process deviation that may ignore arising risks. Moreover, its linear architecture can simplify the interdependencies in the contemporary industrial systems, making the hazard assessment less profound and precise.

Hazard and Operability Study (HAZOP)

Hazard and Operability Study (HAZOP) is a qualitative approach that is systematic and is carried out by a team to determine possible hazards, operational deviations and risks in a given industrial process. It uses guidewords to investigate the ways of failure of design intent to come up, and evaluates the potential impacts, enabling multidisciplinary teams to find out sensitive and intricate safety concerns. The collaborative nature of HAZOP guarantees that all vulnerabilities of the processes have been explored, communication levels among the stakeholders are improved and that preventive measures are developed; it is effective especially in the assessment of complex and interdependent systems.

Strengths of HAZOP

HAZOP is a holistic, qualitative approach, team-based technique, which involves the use of guidewords to methodical analysis of process variations and determine possible risks and operability problems. Its key strength is its capacity to identify multi-dimensional situations using the multidisciplinary brainstorming. The guideword-based method promotes profound investigation of design purpose, working process, and system deviations, which enables practitioners to recognize hidden problems that cannot be reflected in a numerical assessment instrument. Being a cooperative practice, HAZOP improves the communication process, makes the behavior of processes better understood, and results in comprehensive reports of the potential risks and protective measures.

Limitations of HAZOP

Nevertheless, there are also some weaknesses of HAZOP. It is mostly laborious and resource consuming, as it involves involvement of qualified staff which is not always possible in small industries. Lack of a quantitative approach to prioritization creates issues in prioritizing or directly comparing the risks that are identified. Being a qualitative approach, the success of HAZOP requires high proficiency of the facilitator and the competencies of the team members, which may lead to the inconsistencies in the outcomes. Also, in very complex systems, the HAZOP sessions may be long and tedious, which is more likely to dominate any type of oversight, tiredness, and insufficient documentation.

Foundations of Fmea and Hazop

The systematic methodologies of Failure Mode and Effects Analysis (FMEA) and Hazard and Operability Study (HAZOP) are also the major building blocks of the industrial hazard risk assessment since both offer complementary ways of identifying and eliminating risks [10]. FMEA is a bottom-up, semi-quantitative method, which is structured and analyzes potential failure modes, causes, and effects and prioritizes risks using tools such as the Risk Priority Number (RPN) and hence is especially useful during the design, development and in operation. In comparison, HAZOP is a top-down, qualitative and team-based approach whereby guidewords are used to scrutinize process undesired deviations to facilitate the establishment of hazards, operational weaknesses, and technical interrelations that cannot be easily identified by numerical evaluation alone. Theoretical and practical backgrounds of FMEA and HAZOP combined create the grounds of the overall hazard analysis offering a systematic scheme of the improvement of the industrial safety, reliability, and efficiency of processes.

Foundation of Failure Mode and Effects Analysis (FMEA)

FMEA is based on the bottom-up methodical approach to recognizing possible failures and the impact they have on a system, process, or product. It is founded on the idea that a failure could be predicted and prevented by analyzing the individual components or process steps to occur before the failure. FMEA also depends on a systematic process which involves the identification of failure modes, their causes, their potential effects, and priority of these failure modes on semi-quantitative basis like Risk Priority Number (RPN). Its theory has its origins in reliability engineering and proactive risk management, which focuses on proactive risk detection and reduction [11]. The process promotes the cross-functional use of the team, detailed documentation, and repeated assessment, so it has a versatile application in the design, production, and operation phases to enhance safety, dependability, and performance.

Foundation of Hazard and Operability Study (HAZOP)

HAZOP is founded on the qualitative, systematic, and team-based analysis of the deviation of the desired conditions of the process to detect hazards and operability concerns. Originally designed to investigate chemical and process industries, HAZOP employs guide words (including more, less, reverse) to analyse how changes in the process parameters might result in an unsafe or ineffective operation. Its approach has its foundation in process safety management and systems thinking with the focus on shared assessment, cross-disciplinary knowledge and in-depth investigation of possible risks. The methodology of brainstorming that is presented by HAZOP makes sure that the occurrence of complex interaction and minor deviation is diagnosed, recorded and subsequent preventive or corrective actions are taken to counter the problem, thus, it is specifically effective at analyzing the complex and interdependent industrial systems.

1. Failure Mode and Effects Analysis (FMEA)

The United States military developed the first version of Fail Mode and Effects Analysis (FMEA) in 1940s as proactive tool to enhance reliability in system and equipment. Its development over the decades saw FMEA become a broadly used methodology in various industrial sectors, including automotive, aerospace, manufacturing, and healthcare, in order to identify possible failure modes in a systematic manner and reduce the risks prior to the emergence of an operational issue or safety accident. International standards like ISO 9001 and AIAG in the automotive industry have also increased its adoption.

Types of FMEA

FMEA can be classified into several types depending on its application:

- **Design FMEA (DFMEA):** Focuses on identifying potential failures in product design before production, ensuring that design specifications are robust and reliable.
- **Process FMEA (PFMEA):** Evaluates manufacturing or operational processes to detect possible process failures and improve production quality and efficiency.
- **System FMEA:** Examines the overall system-level interactions and failures, often applied in complex, multi-component systems.
- **Other specialized types:** Include software FMEA, service FMEA, and functional FMEA, which are tailored for specific industrial or operational contexts.

Key Components

FMEA relies on a structured framework that typically includes the following components:

- **Failure Modes:** The specific ways in which a component, system, or process can fail.
- **Effects:** The consequences or impact of each failure on system performance, safety, or operations.
- **Causes:** The underlying reasons or root causes for each potential failure.
- **Risk Priority Number (RPN):** A semi-quantitative score calculated by multiplying severity, occurrence, and detection ratings, used to prioritize risks and determine which failure modes require corrective action.

Advantages and Limitations

The strengths of FMEA are its systematic nature, documentation simplicity, the proactive modeling of possible failures and it allows to rank risks, thereby optimising resource utilisation and enhancing the reliability of systems. It promotes the use of cross-functional teams and assists in planning preventive actions. FMEA, however, also has some limitations. It might not be an exhaustive model of complex systems interactions or multi-dimensional failure, it heavily depends on subjective expertise in rating assignments and can be time-consuming in large-scale systems. Also, because it concentrates on a failure mode, as opposed to the system behavior, at times, interdependencies are not considered.

2. Hazard and Operability Study (HAZOP)

The Hazard and Operability Study (HAZOP) was first designed in the 1960s by the chemical industry, specifically the design and operation of chemical plants, to identify the hazards of the process and operational issues in a systematic way [12]. The HAZOP method has over time developed to become a well-known qualitative risk evaluation system that is applicable in different industries like petrochemicals, pharmaceuticals, oil and gas, and manufacturing. Its main aim is to identify possible deviation of the planned operational parameters that may result in safety threat, environmental risks or inefficiencies in production with proactive elimination of such cases before they arise.

Guidewords and Deviation Analysis

HAZOP is based on a systematic method involving the use of guidewords like more, less, no, reverse, and as well as to analyze each parameter of the process systematically to detect nonconformity with the normal operating conditions. The possible causes and effects are considered of every deviation, and it helps identify some risks that would not be easily identified by the traditional analysis. This deviation-oriented methodology enables teams to speculate on the possible scenarios of what-if and is also keen to take into account even the minimal or unrealistic hazard.

Team-Based Qualitative Analysis

One of the major characteristics of HAZOP is the team nature, according to which a multidisciplinary team of specialists in engineering, operations, safety specialists, and designers reviews the process. This qualitative analysis would foster various opinions, thorough discussion and exchange of knowledge which adds depth and precision to hazard identification. The facilitator leads the discussion, makes sure that all the process parameters are systematically covered and records findings, which are to be used in reducing risks [13].

Strengths and Constraints

HAZOP has the following strengths, it is comprehensive in defining multi-dimensional and complex hazards, has collaborative qualities that promote thorough evaluation of risks, and adaptability to many industrial processes. It can also be used successfully to identify operational deviations and the existence of subtle safety concerns that otherwise might not be observed using solely quantitative approaches. Nevertheless, HAZOP is not without its limitations: it is a time-consuming process that uses resources and depends on the knowledge and experience of the team. Additionally, it is qualitative and therefore, it is hard to prioritize risks quantitatively, and meetings may take a long and strenuous time in highly complex systems, which may be resulting in fatigue or oversight.

Complementary Nature of Both Techniques

Two commonly used risk assessment approaches to use in an industrial system are Failure Mode and Effects Analysis (FMEA) and Hazard and Operability Study (HAZOP), which have respective methods, advantages, and disadvantages. Although they are effective on their own, their real potential is realized when used in a supplementary and combined way as each technique fills in areas of weaknesses caused by the other technique [14].

FMEA is a bottom-up, semi-quantitative method which concentrates on the possible failure modes at component, process or system level, evaluates their cause and effects and ranks the risks using the risk Priority number (RPN). The well-organized process enables it to be well documented, systematically analyzed and easily prioritized the risks, rendering it very useful in the early design phase, preventive maintenance and resource allocation.

Nevertheless, FMEA is usually not as profound to reveal intricate interactions, process exceptions, or operational susceptibilities that become manifest when industrial systems are in motion.

Conversely, HAZOP is a qualitative, top-down, and team-based approach which looks at design intent violations through guidewords and brainstorming. HAZOP is very effective in identifying the operational aberrations, deviation of processes and hazards that cannot be identified entirely by the use of purely numerical analysis. It promotes multifunctional conversations, where it is possible to define the hidden dangers of process variability, human factors, or systemic interactions. However, quantitative prioritization is not inherently embedded in HAZOP, and therefore, it is difficult to prioritize the hazards objectively or to efficiently allocate mitigation resources.

FMEA and HAZOP can be seen as complementary because of how well they can respond to one another, given their limitations. Development of the qualitative, deviation-oriented perspective of HAZOP and the semi-quantitative prioritization of FMEA can enable industries to have a comprehensive risk assessment. FMEA can offer quantifiable indicators on making decisions, whereas HAZOP can be used to check that all possible deviations, including high-impact but low-probability hazards, have been considered. Collectively, they allow the full identification of the hazards, proper risk prioritization, and formulation of effective mitigation strategies, which makes the combined strategy especially useful in complex and automated, and highly interdependent industrial systems.

Essentially, FMEA and HAZOP are not contrasting methodologies but rather complementary tools and the quantitative, systematic nature of FMEA is used to complement the qualitative, diagnostic nature of HAZOP to lead to improved safety, reliability and operational stability of industrial activities.

Integrated Fmea–Hazop Frameworks: A Conceptual Overview

As the complexity of industrial systems increases, general FMEA or HAZOP approach frequently is not sufficient to offer a complete view of risk assessment. Although FMEA provides a quantitative, semi-structured method of identifying failure modes and ranking risks, it has the potential to miss more complicated deviations in processes or between processes. HAZOP on the other hand is good at qualitative identification of hazards via guide word based deviation interpretation but does not have quantitative prioritization. In order to overcome these shortcomings, the integrated FMEA-HAZOP structures have been introduced, which incorporates the mutual capabilities of the two approaches to a more solid, dependable, and thorough hazard and risk evaluation [15].

Rationale for Integration

The integration of FMEA and HAZOP aims to:

1. Improve the identification of hazards through the detailed qualitative analysis of HAZOP and systematic evaluation of failures of FMEA.
2. Use FMEA semi-quantitative RPN method to prioritize the risks and record the deviations in operations by HAZOP.
3. Offer a systematic framework that is proactive (via FMEA) and also diagnostic (via HAZOP) keeping in mind any critical hazard is not ignored.
4. Enhance resource distribution by targeting corrective measures on high-priority hazards that are revealed during combined analysis.

Framework of the Integrated FMEA–HAZOP Approach

The combined FMEAHAZOP model integrates both the qualitative and quantitative prioritization of FMEA and HAZOP to increase the trustworthiness and security of complicated systems. The framework has six systematic steps that help in identifying, evaluating, assessing, and managing risks [16].

1. System and Process Definition

The initial level defines a starting point by clearly defining the boundaries of the system, flow of processes, components, sub-systems and the operational parameters. This stage specifies the design intent, anticipated operating conditions and initial safety and performance requirements so that all members of the analysis team understand what they are.

2. Preliminary Hazard Identification

This step is implemented in order to determine the possible hazards and failure modes based on historical incident, expert opinion, pre-assessment and system knowledge. Early identification of hazards can help bring to focus the most sensitive aspects of the system prior to the in-depth analysis.

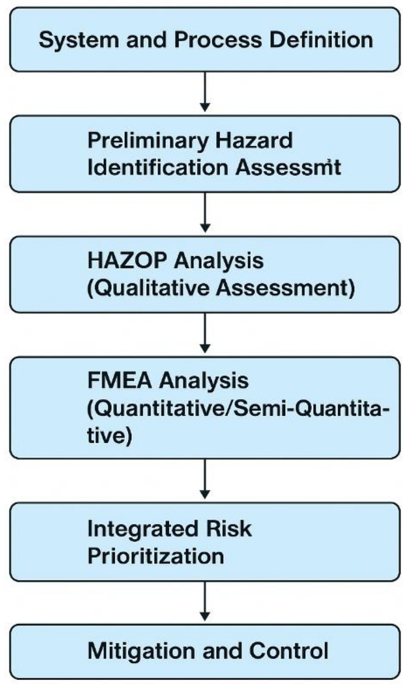

Figure 1: Framework of the Integrated FMEA–HAZOP Approach

1. HAZOP Analysis (Qualitative Assessment)

A formal HAZOP study is carried out, and standard guidewords (i.e., more, less, no, reverse) are employed to explore the potential deviation of the process in a systematic way. Under each deviation, the team will analyze the cause, consequences and any form of safeguards and operational vulnerability. A detailed map of plausible hazard scenarios is the outcome of this qualitative analysis [17].

2. FMEA Analysis (Quantitative/Semi-Quantitative Assessment)

The failure modes and deviations detected during the HAZOP phase are considered with the help of FMEA parameters Severity (S), Occurrence (O), and Detection (D). All the failure modes are rated and the Risk Priority Number ($RPN = S \times O \times D$) is calculated to represent the amount of risk. This phase explains the most severe failure modes that require an immediate mitigation.

3. Integrated Risk Synthesis and Prioritization

The information obtained with the help of both HAZOP and FMEA is combined to create a detailed risk portrait. Cross-validation provides consistency and removes hazards that are not taken into account. The joint findings can be used to prioritize risks evidence-based so that high-severity deviations as well as high-RPN failure modes are addressed [18-20].

4. Mitigation Planning and Control Implementation

According to the combined evaluation, specific remedial measures are proposed - either engineering overhaul, enhanced protection, or operational controls or surveillance measures. Risk mitigation should be effective throughout the system lifecycle by having continuous performance monitoring, periodic updates as well as feedback loops.

Conclusion

Combined FMEA-HAZOP models constitute a major step towards an improved method of industrial hazard risk assessment by merging the structured, semi-quantitative strong sides of FMEA with the qualitative diagnostic power of HAZOP. This form of integration can overcome the shortcomings of single approaches, considering a more comprehensive analysis of a complex industrial system of interdependent processes, automation and changing operational situations. The intellectual model presented in this review illustrates a systematic process of work, i.e., the definition of the system and initial hazard identification, qualitative analysis using HAZOP, risk quantification using FMEA, synthesis and mitigation planning. The utilization of these combined solutions leads to the better identification of hazards, the enhancement of prioritization of risks, efficient distribution of available resources, and the increased safety and reliability of the overall operations. Although they have benefits, issues exist that include the intensity of resources, reliance on professional opinion, and the complexity that may arise in large systems. The next way to advance these frameworks is to concentrate on digitalization, AI-assisted evaluations, and adaptive integration schemes to enhance them and allow industries to proactively handle risks, adhere to the safety standards, and sustain sustainable and resilient operations.

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