Review Article

Hybrid Approach to Overcoming Failure Mode and Effect Analysis Deficiencies in Complex Systems: Comprehensive Review

Joseph J. Akpan[1,2*], Ikuobase Emovon[1], Chinedum O Mgbemena[1] and Modestus Okwu[1]

[1]Department of Mechanical Engineering, Federal University of Petroleum Resources, Effurun, Delta State, Nigeria; [2]Department of Mechanical Engineering, Federal University of Technology, Ikot Abasi, Akwa Ibom State, Nigeria.

Abstract | The deployment of Failure Mode and Effects Analysis (FMEA) in industry has continued to be one of the most commonly adopted practices in the evaluation of failure modes and the resolution of risk within industrial settings. The Risk Priority Number (RPN) model used in this technique helps in objective ranking and improvement of the critical risks that require immediate and proper risk prioritization. Technical professionals and researchers have come up with hybrid models designed to advance the accuracy and applicability of these decision-making techniques. The literature review reviews peer-reviewed articles published from 2020 to 2025, considered relevant to the development and projection of FMEA and its mix approaches. The work reviews different new approaches targeted at addressing the shortfalls of traditional FMEA, also evaluating their use in industrial settings. The review was able to deliver answers to four important research questions: (i) Which industry is the most successful in using FMEA and its variants of hybrids? (ii) What is the growth rate in the development of these integrated approaches? (iii) Who are the most cited authors/journals in the application of the method, and (iv) What are the journals/publishers that have been most instrumental in spreading the research as concerns hybrid FMEA techniques throughout the time frame of the review? This evaluation offers insight into the current research and contributions of the innovations. The scholarly work also empties the current landscape of FMEA, identifying the promising direction of future research and application in the field.

Received | February 25, 2026; **Accepted** | March 28, 2026; **Published** | May 23, 2026
***Correspondence** | Joseph J. Akpan, Department of Mechanical Engineering, Federal University of Petroleum Resources, Effurun, Delta State, Nigeria; **Email:** akpanjohn015@gmail.com, emovon.ikuobase@fupre.edu.ng
Citation | Akpan, J.J., I. Emovon, C.O. Mgbemena and M. Okwu. 2026. Hybrid approach to overcoming failure mode and effect analysis deficiencies in complex systems: Comprehensive review. *Smart Technologies in Science and Engineering,* 1(1): 23-45.
Keywords |Failure mode and effect analysis, Fuzzy logic, Risk priority number, Risk assessment, Hybrid, Reliability

Introduction

Failure Mode and Effects Analysis (FMEA) is one of the widely accepted risk assessment techniques across industry for proactive identification of potential causes of system, components, or process failure. First established in the 1940s and adopted later in the 1960s by NASA, the Failure Mode and Effects Analysis has become a household name and an acceptable industrial tool for safety and reliability enhancement, Alber (2016).

The FMEA procedure enables the conduct of an in-depth review of components, systems, and operations, helping stakeholders to establish every possible failure mode, starting from top down to the subsystem level, giving access to the identification of potential consequences (Peeters *et al.*, 2018). The analysis systematically examines underlying factors that can trigger failure, starting from mechanical stresses, environmental forces, and electrochemical and thermal exposures according to Umofia and Shafiee (2017). In applying FMEA, industries can develop a pre-emptive strategy to mitigate these risks, thereby improving operational integrity through improved system performance. The worth of FMEA is particularly significant in managing complex and high-risk systems and work (Samir *et al.*, 2017).

As a practical medium, FMEA assists industries to have a fair knowledge of component vulnerabilities, their failure patterns, damage build-up, and the impact of external stresses. FMEA is instrumental not only in preventing catastrophic failures but can also act as optimizing maintenance schedules in managing asset life cycles. In its right application, FMEA can reveal weaknesses in design, assembly, manufacturing, material processing, or service anomalies.

The understandings and perceptions derived from FMEA are invaluable, resulting in an improved design, better material selection, and more efficient process controls. These can together foster a safer and more productive industry. Moreover, FMEA is not limited to prevention; it also serves as a more needed tool for post-failure investigation. In analyzing the root cause and sequence of events that led to a failure, firms and industrial operators can build more resilient systems and components that are less susceptible to similar issues in the future (Petrovskiy *et al.*, 2015).

The cycle of this constant improvement is vital to the development of the industry and to the preservation of the high level of safety required. The suppleness of FMEA defines its importance in the adaptability of the method, and it can be used on different levels of detail. It can also be used in the general analysis of the system or a detailed study of particular aspects and units; this is why it is considered an effective tool in the risk management toolbox of all industries.

Traditionally, Failure Mode and Effects Analysis (FMEA) is based on the determination of a Risk Priority Number (RPN) to determine how critical and risky a given failure mode is. However, a predictable RPN approach has significant disadvantages, such as the Lack of Intuitive Readability, Steep Learning Curve, Limited Error Handling, Stack Management Complexity, Difficulty in Manual Calculation, limited adoption, and Not Ideal in Symbolic Manipulation when used in applications to actual risk situations, and so can be less efficient in practical risk assessment.

In response to the known and established shortcomings of conventional FMEA, a wealth of integrated methodologies has emerged in recent literature. This research conducts a systematic review of 200 publications (2020-2025) to evaluate these novel approaches that employ advanced decision-making techniques in the improvement of risk assessment. The investigation is guided by some research questions, including (1) Which industries are at the forefront of adopting both standard and hybrid FMEA practices? (2) What are the trends and developments characterizing the evolution of these integrated approaches? (3) Who are the most significant and regularly cited academics in this field? (4) Which journals lead in the role of promoting and disseminating research on hybrid FMEA techniques during this period? Apart from emphasising the advantages of these alternative methods over the traditional Risk Priority Number (RPN) approach, this review is intended to be a practical guide and a scholarly resource for researchers, practitioners, and risk analysts aiming to apply FMEA more effectively. This work additionally sheds light on the emerging trends in risk analysis methods and proposes future research directions, offering a deeper understanding of the shifting landscape of risk assessment practices.

Categories of failure mode and effects analysis

Failure Mode and Effects Analysis (FMEA) is classified based on the type of application, thus this leads to six different classes, as shown in Figure 1.

Concept failure mode and effects analysis (CFMEA)

The Concept FMEA is used in the initial conceptual phase, before hardware is defined. This helps in analyzing potential failures in a concept's intended functions and the interactions between different systems and their elements.

Design failure mode and effects analysis (DFMEA)

The design FMEA focuses on the product design itself. It is a proactive method for identifying and eliminating potential failure modes in components, subsystems, or systems during the design phase. The aim is to ensure the design meets all functional requirements, choose the best design solution, and build a formal record for future use, ultimately preventing design flaws from affecting the customer (Rasu 2023).

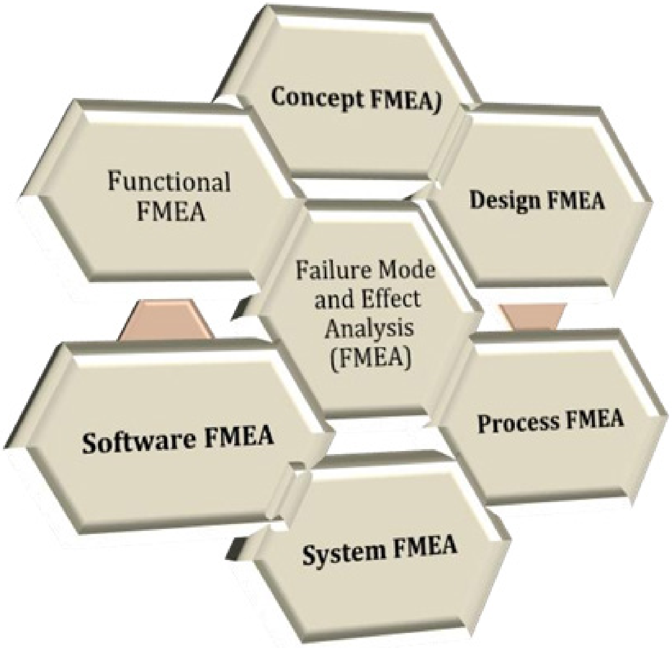

Figure 1: *The classes of failure mode and effect analysis.*

Process FMEA (PFMEA)
This method aims at identifying potential failures in manufacturing and assembly. Manufacturing-related failures are often visual or dimensional, while the failures in assembly involve relational errors, loose, or missing parts (Pantazopoulos and Tsinopoulos 2005).

System FMEA (SFMEA)
The system FMEA takes a holistic view, examining the entire system to ensure all components and subsystems interact harmoniously. This method focuses on eliminating failures that threaten overall system performance and safety.

Software failure mode and effects analysis (SFMEA)
This is a controlled process for identifying and assessing potential failures in software design and development. The method guarantees the software's reliability and quality.

Functional failure mode and effects analysis (FMEA)
Functional FMEA examines how a system functions to predict where it might fail and the consequences. This proactive analysis is critical for maintaining reliability, safety, and performance (Häring 2021).

The review of literature
Table 1, is a summarizes research from 2020 to 2025, offering a systematic review of how integrated Failure Mode and Effects Analysis (FMEA) techniques have been applied to evaluate risk and improve reliability in diverse industries.

Table 1: *The systematic review breakdown.*

Author (s)	Year	Focus/ Area	Methodology/ Model	Contributions/Finding
Wang *et al.*	2020	Subsea Christmas tree systems	Dynamic Bayesian Network	Vertical systems are more reliable; preventive maintenance is emphasized
Liou *et al.*	2020	SMPS manufacturing	NBWM and NWASPAS	Improved RPN accuracy for better risk identification
Bhattacharjee *et al.*	2020	General risk assessment	Interval number-based logistic regression, FMEA	Refined RPN by adjusting the weightage of S, O, D
Huang *et al.*	2020	General FMEA evolution	Literature review, Fuzzy inference, grey theory	Identified gaps; proposed alternatives to traditional RPN
A. Rahimi, H. Khosravi	2020	Construction safety	Fuzzy FMEA, DEMATEL, ANP	Multi-phase fuzzy model for construction risk prioritization
Xinhong *et al.*	2020	Urban oil and gas pipelines	Fuzzy TOPSIS	Prioritized corrosion risks; stressed proactive management
Ayyildiz *et al.*	2020	Petrol station location selection	Spherical fuzzy AHP-WASPAS	Handled uncertainty; validated via sensitivity analysis
Sałabun	2020	Decision analysis	MCDA benchmarking (TOPSIS, VIKOR, COPRAS, PROMETHEE II)	Compared ranking similarities and parameter impacts

Table continues on next page................

Author (s)	Year	Focus/ Area	Methodology/ Model	Contributions/Finding
Fattahi *et al.*	2020	General risk assessment	Fuzzy MCDM, FMEA	Replaced RPN with weighted criteria; improved decision-maker alignment
Pang *et al.*	2020	Subsea wellhead connector	Fault tree analysis, fuzzy logic, Markov model	Validated reliability model with real-world data
Simsek and Ic	2020	Concrete plant safety	Fuzzy-rule-based risk assessment	Identified high-risk areas; validated via employee feedback
Beldek *et al.*	2020	Project selection in consultancy	FAHP, fuzzy MCDM	Prioritized criteria; reduced uncertainty
Sagnak *et al.*	2020	Furnace failure risk	Prospect Theory, Fuzzy AHP, TODIM	Ranked failure modes; relied on expert judgment
Yücenur *et al.*	2020	Pharmaceutical quality control	FMEA, Fuzzy ranking	Reduced risk by 72%–90%; improved safety
Bongo	2020	Wooden-hulled boat construction	Fuzzy FMEA	Identified wood/design risks; improved safety standards
M. Yazdani, S. Zarandi	2020	Failure mode identification	MCDM, TOPSIS, and DEMATEL	Integrated TOPSIS and DEMATEL to identify critical failure modes with improved decision-making accuracy.
H. Tavakkoli-Moghaddam *et al.*	2021	Risk prioritization	Fuzzy Logic, AHP, TOPSIS	Improved accuracy in FMEA ranking through fuzzy hybridization
Tripathi	2021	Photovoltaic systems	Fuzzy logic-driven FMEA	Enhanced reliability and maintenance prioritization
Yener and Can	2021	General risk assessment	Intuitionistic fuzzy logic and advanced MCDM	Improved failure mode ranking accuracy
Haddad *et al.*	2021	Supplier selection in oil and gas	Fuzzy TOPSIS	Focused on HSE criteria; improved high-risk decisions
Koohathongs *et al.*	2021	Multimodal transport routes	Fuzzy risk assessment and DEA	Validated with the Thailand-Cambodia case study
Shamsuzzoha and Shamsuzzaman	2021	General risk assessment	Fuzzy TOPSIS	Improved failure mode ranking accuracy
Lestari *et al.*	2021	Wiring Harness Assembly	Fuzzy FMEA, Fishbone Diagram	Identified insulation damage as critical; proposed mitigation strategies
Harith *et al.*	2021	Boiler Systems	FMEA and FAHP	Improved risk prioritization beyond traditional RPN
S. K. Ghosh, P. Roy	2021	Safety science	FMEA, VIKOR	VIKOR enhances decision-making in risk prioritization
Mardani *et al.*	2021	Iranian Gas Plant	Pythagorean Fuzzy K-means and PF-VIKOR	Enhanced failure mode analysis under uncertainty
Gupta *et al.*	2021	Centrifugal Pumps	FMECA, Fuzzy Logic, and Dempster-Shafer	Validated an advanced model for reliability analysis
Y. Chen, Z. Li	2021	Knowledge-based systems	DST-Fuzzy FMEA, Fuzzy-D Numbers	Dempster–Shafer theory enhances evidence-based risk modeling
S. Patel, K. Mehta	2021	Supply chains	FMEA + AHP-PROMETHEE, Fuzzy AHP, IoT	IoT and MCDM integration for dynamic supply chain risk mitigation
Efe and Efe	2021	Construction Risk	QFD, Interval Type-2 Fuzzy Sets, Bayesian, and VIKOR	Innovated QFD for better risk assessment
R. Alizadeh, B. Kiani	2021	Intelligent manufacturing	FMEA, Entropy, PROMETHEE	Entropy-based weighting improves objectivity in FMEA
Oreko *et al.*	2021	Egbin Thermal Power Station (Nigeria)	FST and GRA	Optimized maintenance and improved reliability

Table continues on next page...............

Author (s)	Year	Focus/ Area	Methodology/ Model	Contributions/Finding
Alvand *et al*.	2021	Construction Projects	FMEA, SWARA, and WASPAS	Outperformed conventional risk assessment methods
Puspitasari and Yuwono	2022	Operational Risk	Fuzzy Logic and House of Risk (HOR)	Identified key risk agents; proposed communication-based mitigation
Bilgili *et al*.	2022	Renewable Energy (Turkey)	IF-TOPSIS	Solar energy ranked highest; investment cost is most critical
M. Ghasemi, F. Hashemi	2022	Healthcare	FMEA, Fuzzy Logic, DEMATEL	Tailored healthcare risk assessment using fuzzy DEMATEL
Belouaar *et al*.	2022	E-commerce Websites	Fuzzy TOPSIS	Improved decision-making and user preference handling
F. Ali, M. Khan	2022	Renewable energy	FMEA, SWARA, VIKOR, ROC, and CoCoSo, SF-WASPAS	Hybrid models optimize risk prioritization in energy systems
Pouyakian *et al*.	2022	Food Processing Industry	Fuzzy MCDM	Optimized risk control measures
Hassan *et al*.	2022	Petroleum Pipelines (Nigeria)	Fuzzy Logic and Grey Theory	Refined hazard detection under uncertainty
Alazemi *et al*.	2022	Supply Chain	Fuzzy TOPSIS and Machine Learning	Achieved 10.3% efficiency improvement
Haimer *et al*.	2022	Healthcare (Morocco)	Fuzzy Logic and FMEA	Improved patient safety and decision-making
Stoumpos and Theotokatos	2022	Marine DF Engines	FMECA and Digital Twin	Refined safety analysis for operational changes
Biswas *et al*.	2022	MCDM	ABAC Method	Addressed rank reversal; improved transparency
Ge *et al*.	2022	Subsea Compressor Systems	FMEA, FAHP, and Fuzzy Logic	Identified high-risk components; reduced uncertainty
T. Oliveira, M. Costa	2022	AI applications	Decision Trees, ANN	Neural networks and trees boost predictive risk modeling
Aswin *et al*.	2022	Process Industries	FMECA, Fuzzy Logic, and Grey Theory	Demonstrated flexibility in uncertainty handling
Marhavilas *et al*.	2022	Petrochemical Industries	MCDM, AHP, HAZOP, and DMRA	Hybrid safety framework using color-coded maps
Hu and Lin	2022	Property Concealment	MCGDM, Z-numbers and ELECTRE-III	Improved accuracy
Ervural Ayaz	2023	Manufacturing	Data-driven FMEA, real-time analytics, hybrid methods	Improved risk assessment
N. Singh, A. Sharma	2023	Production research	Fuzzy Logic, ANP	ANP-fuzzy hybrid enhances interdependency modeling in FMEA
Kumari	2023	Effluent treatment plants	Fuzzy-based MCDM	Optimized risk assessment in humid regions
Cardiel and Serrato	2023	Textile industry	Fuzzy logic evaluation system	Refined risk prioritization
Lonfinmaki *et al*.	2023	Welding (mild steel joints)	ANFIS, AI, Fuzzy logic	Enhanced tensile strength and hardness prediction
Lee *et al*.	2023	Urban water systems	Fuzzy MCDM integrated framework	Promoted sustainability
Liu Z. *et al*.	2023	Aerospace (aircraft power systems)	Fuzzy linguistic sets, hybrid weighting	Improved risk identification
Durrani and Zeesan	2023	Industrial risk	FMEA, questionnaire surveys	Identified logistics, health, and safety as critical risks
B. Zhang, L. Huang	2023	Information sciences	IT2F-FMEA, Petri Nets, DEMATEL-MABAC, ORESTE	Interval type-2 fuzzy sets improve uncertainty handling
Ceylan *et al*.	2023	Ship engines	Fuzzy FMEA	Assessed turbocharger fouling impacts

Table continues on next page...............

Author (s)	Year	Focus/ Area	Methodology/ Model	Contributions/Finding
Rustono *et al.*	2023	Deep-sea oil extraction	Risk analysis	Workplace accidents are identified as the highest risk
Tang *et al.*	2023	Manufacturing, aviation	Dempster–Shafer theory, grey relational projection	Eliminated uncertainties in risk assessment
Küçüktopçu *et al.*	2023	Poultry farming	Fuzzy logic AI	Improved weight prediction and efficiency
Altunhan *et al.*	2023	Natural gas pipelines	ANFIS and BIM	Enhanced decision-making with hybrid learning
Xiao *et al.*	2023	Subsea control systems	FMEA and FFTA	Identified system vulnerabilities
Meng *et al.*	2023	Electric Power Cloud	MCDM Fuzzy Type-2 VIKOR.	Case Study Validation, and Sensitivity and Comparative Analysis
Panyukov *et al.*	2024	Risk management	Advanced algorithm in FMEA	Optimized monitoring and audits
Vitor Anes, António Abreu	2024	Risk assessment	FMEA, ROC, CoCoSo	Integrated hybrid model for more robust risk evaluation
Al-Mhdawi *et al.*	2024	OandG construction	Fuzzy-Based FMEA	Identified 41 risks; PPE non-compliance most critical
Razzaq *et al.*	2024	Manufacturing	Fuzzy-FMEA	Improved quality control and reliability
M. Bougofa *et al.*	2024	Automotive industry	FAHP, Rough TOPSIS, PROMETHEE, EFMULTI-MOORA	Multi-layered hybrid model for criticality assessment
Sabripoor *et al.*	2024	Organ transplant	Fuzzy MCDM	91.67% agreement with expert rankings
J. Liu *et al.*	2024	Oil pipelines	DBNs and IT2FS	Enhanced failure prediction and mitigation
Ma *et al.*	2024	Decision-making	Interval-Valued Fermatean Fuzzy Sets and Bonferroni mean	Improved uncertainty handling
Tao *et al.*	2024	SCM electrical systems	Digital Twin and DBN	Sensor-driven failure prediction
Shao *et al.*	2024	Hydrogen storage	Fuzzy MCDM, Kano, and FMEA	Prioritized health and safety
Beiranvand	2024	Earth dam construction	Two-stage fuzzy reasoning	Enhanced environmental risk identification
Yuan *et al.*	2024	Downhole safety valves	Bow-tie and ETAL	Prioritized 14 risks
Kan *et al.*	2024	Submarine pipelines	GRP-VIKOR and IT2FS	Improved decision-making via cooperative game theory
Yu *et al.*	2024	LNG storage tanks	FFCCS-FMEA, FFS and CoCoSo	Better risk ranking under uncertainty
Puppala and Manoharan	2024	Blockchain mining	VIKOR-based model	Optimized miner selection
Radulescu and Radulescu	2024	IoT platform selection	Hybrid MCDM (SAW, TOPSIS, VIKOR, COPRAS, BWM)	Enhanced ranking precision
Ali *et al.*	2024	Petroleum industry	Fuzzy VIKOR and Shannon entropy	Prioritized health and safety risks
Tian *et al.*	2024	EV charging procurement	CTriIT2F-LDA-EDAS	Streamlined supplier evaluation
J. Park, S. Lee	2024	Cybersecurity	FMEA + ROC + CoCoSo, Fuzzy AHP, DST, CVSS	Comprehensive cybersecurity risk assessment using hybrid FMEA
Mishra *et al.*	2024	Waste recycling plant	FFSs, MEREC, SWARA, and MARCOS	Precise site selection
Q. Ma *et al.*	2024	Risk assessment	q-rung orthopair fuzzy cognitive maps and TOPSIS	Improved failure mode prioritization
Z. Xiao *et al.*	2024	FSRU emergency response	IFHWED-FMEA, AHP and fuzzy algorithms	Enhanced maritime preparedness
Turgay	2024	System reliability	FMAGT and DEA	Cost-effective FMEA sequence analysis
Chakhrit *et al.*	2024	Automotive industry	FMEA and ANFIS	Real-time risk evaluation

Table continues on next page................

Author (s)	Year	Focus/ Area	Methodology/ Model	Contributions/Finding
Chang *et al*.	2024	Crawler crane assessment	DEA and 2-tuple fuzzy model	Refined risk rankings
Lingras *et al*.	2025	Software systems	Software FMEA, RPM, and HAZOP	Improved ADAS risk assessment
Thomas	2025	Manufacturing	Dynamic FMEA and AI/ ML/IoT	Proactive risk management
Chen *et al*.	2025	Complex systems	Fermatean fuzzy Z-number and Muirhead mean	Enhanced risk prioritization
Kumar	2025	MCDM methods	AHP, TOPSIS, AI, block-chain, and big data	Reviewed challenges and integrated solutions
James *et al*.	2025	LNG leak safety	ANFIS and Bow-tie	Improved prediction and safety

The overview and analysis

Industries with the most active application of the hybrid FMEA 2020-2025

Between 2020 and 2025, Failure Mode and Effects Analysis (FMEA) evolved significantly through hybrid methodologies, integrating fuzzy logic, Bayesian networks, and multicriteria decision-making (MCDM), etc. These innovations have enhanced risk prioritization, predictive accuracy, and decision-making under uncertainty across a wide range of industries:

- Oil, gas and energy (OG and E): Subsea Systems: Wang *et al*. (2020) and Shafiee and Animah (2022) applied Dynamic Bayesian Networks and FMEA-MCDA for reliability in high-pressure/ high-temperature environments.
- LNG and Refineries: Yu *et al*. (2024) introduced FFCCS-FMEA using Fermatean fuzzy sets; James and Renjith (2025) combined ANFIS with Bow-tie for LNG leak prediction; multi-fuzzy logic systems were used for refinery risk.
- Pipeline Safety: Xinhong (2020), Efe and Efe (2023), and Kan *et al*. (2024) used fuzzy TOPSIS, q-ROFN QFD, and GRP-VIKOR, respectively, for pipeline hazard detection and prioritization.
- Gas Plants and Oil Depots: Haddad *et al*. (2021), Koohathongs *et al*. (2021), and Liu *et al*. (2023) applied fuzzy TOPSIS, DEA, and fuzzy FMEA for risk ranking.
- Energy Projects: Shamsuzzoha and Shamsuzzaman (2021) ranked renewable energy initiatives using fuzzy logic and MCDM.
- CO_2 and Emissions: Ebadzadeh *et al*. (2023) and Kumari *et al*. (2023) used fuzzy entropy and WASPAS for environmental risk assessments.

Construction and infrastructure (CON and INF)

Simsek and Ic (2020), Beldek *et al*. (2020), and Chen *et al*. (2025) validated fuzzy-rule-based assessments and FAHP for project selection. Sagnak *et al*. (2020) and Pang *et al*. (2020) integrated TODIM, fuzzy AHP, fault tree analysis, and Markov modeling for reliability and failure mode ranking. Studies of Yücenur *et al*. (2020), Bongo (2020), and Moghaddam *et al*. (2021) applied fuzzy-GRA and SWARA-WASPAS for construction risk evaluation. Kumar (2025) reviewed traditional and AI-based MCDM models for infrastructure decision-making.

Manufacturing and industrial systems (MAN and IND)

Liou *et al*. (2020), Bhattacharjee *et al*. (2020), and Huang *et al*. (2020) introduced Neutrosophic logic, interval logistic regression, and grey theory for SMPS and general manufacturing risk.

- Thomas (2025) emphasized AI, ML, and IoT for dynamic FMEA in manufacturing.
- Chen *et al*. (2025) applied fuzzy Z-numbers and Muirhead mean for complex system prioritization. Relkar (2021) developed a weighted RPN framework for machinery maintenance.
- Studies of Ivančan and Lisjak (2021), Sari (2021), and Lestari *et al*. (2021) demonstrated entropy-weighted FMEA and fuzzy clustering in assembly and boiler systems. Tao *et al*. (2024) and J. Liu *et al*. (2024) used fuzzy reasoning and Bayesian models for fault prediction in textile and electrical systems.

Transportation and automotive (TRA and AUT)

- Chang *et al*. (2024) applied DEA and 2-tuple fuzzy models for crawler crane risk assessment.
- Tian (2024) developed CTriIT2F-LDA-EDAS for supplier evaluation in EV charging stations.
- Haddad *et al*. (2021) and Koohathongsumrit and Meethom (2021) addressed transportation risk using fuzzy TOPSIS and DEA. Lingras *et al*. (2025) proposed Software FMEA with RPM and HAZOP for ADAS systems. Sarafraz (2023) and

Al-Mhdawi (2024) tackled autonomous shipping and oil and gas safety hazards.

Healthcare and pharmaceuticals (HEA and PHA)
Yücenur *et al.* (2020) applied fuzzy FMEA in pharmaceutical risk reduction. Healthcare sterilization safety was addressed by El Haimer *et al.* (2022) using fuzzy logic. Bhardwaj *et al.* (2024) and Ma *et al.* (2024) optimized organ transplant and hydrogen storage decisions using neural networks and Bonferroni operators.

Environmental and renewable energy (ENV and REN)
Tripathi *et al.* (2021) improved photovoltaic system reliability. Offshore wind site selection was enhanced using Type-2 Neutrosophic MABAC, Deveci *et al.*, 2021. Rustono *et al.* (2023) applied reliability-centered maintenance for workplace safety. Renewable energy evaluation was supported by IF-TOPSIS Bilgili *et al.* (2022).

Consumer and E-commerce (C'MER and E-CO)
E-commerce ranking was refined using fuzzy MCDM Belouaar *et al.*, 2022). Food industry risk control was improved via fuzzy logic, Pouyakian *et al.*, (2022). Urban planning benefited from spherical fuzzy AHP-WASPAS in the work of Ayyildiz *et al.* (2020).

Technology and AI integration (TEC and AI)
Puppala and Manoharan (2024) applied VIKOR for blockchain miner selection. Radulescu and Radulescu (2024) developed an IoT platform selection framework using SAW, TOPSIS, VIKOR, COPRAS, and BWM. Lonfinmakin *et al.* (2023), Ervural and Ayaz (2023), and Küçüktopçu *et al.* (2023) used ANFIS and fuzzy expert systems for predictive analytics in agriculture and welding. Machine learning-enhanced supply chain models were explored by Alazemi *et al.* (2022). Marine engine analysis via digital twins was demonstrated by Stoumpos and Theotokatos (2022).

Methodological and cross-industry contributions (METand CRO-IN)
Sałabun (2020) benchmarked MCDA models; Zhu *et al.* (2022) and Samal and Dash (2022) refined TOPSIS and fuzzy rough methods. Chennoufi and Chakhrit (2024) and Madanchain and Taherdoost (2023) provided foundational guides for LOPA and FMECA. Novel methods like ABAC in Biswas *et al.*, (2022), fuzzy-grey FMECA in Aswin *et al.* (2022), and PF-MABAC, Aydin *et al.* (2022), pushed methodological boundaries. Hybrid safety frameworks by Marhavilas *et al.* (2022) and Z-number-based property risk models by Z. Hu and J. Lin (2022) continued refinement. Chakhrit *et al.* (2024) applied ANFIS for real-time automotive risk evaluation. Rani *et al.* (2022) and Deveci *et al.* (2023) used IVFFSs and fuzzy VIKOR for urban transport and e-waste recycling.

Failure Mode and Effects Analysis (FMEA) and its associated methodologies have emerged as essential tools for proactive risk and reliability management across various industries. These approaches enable organisations to identify potential points of failure, evaluate their potential impact, and implement preventive measures before issues escalate. With the increasingly growing role of safety, quality, and operational reliability as the key drivers of growth, the use of FMEA and such analytical models has experienced an impressive increase, since it assists in eliminating uncertainty and delivering a more dependable RPN. This interest has also been seen to spill over to the adoption of more advanced and integrated methods, including Fuzzy Logic, Multicriteria Decision Analysis (MCDA), and Fault Tree Analysis (FTA), among others. The extent to which these tools are currently being used and the effect they are having on the mitigation of risks and the outcomes achieved have become a major area of interest to organisations that are keen on boosting their risk management plans. The engagement of the industry in these techniques in 2020–2025, as represented in Table 2, is based on a summary of the reviewed literature.

The growth trends of the FMEA hybrid approach between 2020-2025
The technological growth and advancement across the industry are leading to the development of more intelligent, adaptive, and data-centric decision-making systems. These novelties in risk modeling and real-time analytics are bringing in a paradigm shift in risk management, uncertainty, and complexity across industrial sectors. This model shift is a direct function of progress in decision-support systems powered by hybrid FMEA frameworks and sector-specific customizations, which improve precision and application. As a result, such intelligent systems are becoming vital for contemporary organizational resilience, a trend documented in Table 3.

Table 2: *Industry engagement and its frequency of application.*

Authors	Industry	Frequency
Wang *et al.*, Shafiee and Animah, Yu *et al.*, James and Renjith, Xinhong, Efe and Efe, Kan *et al.*, Haddad *et al.*, Koohathongs *et al.*, Liu Y. *et al.*, Shamsuzzoha and Shamsuzzaman, Ebadzadeh *et al.*, Kumari.	Oil, Gas, and Energy (OG and E)	14
Simsek and Ic, Beldek *et al.*, Chen *et al.*, Sagnak *et al.*, Pang *et al.*, Kumar	Construction and Infrastructure (CON. and INF)	9
Liou *et al.*, Bhattacharjee *et al.*, Huang *et al.*, Thomas, Chen *et al.*, Relkar, Studies, Tao and Liu J.	Manufacturing and Industrial System (MAN andIND)	11
Chang *et al.*, Tian, Haddad *et al.* , Koohathongs *et al.* , Lingras *et al.* and Sarafraz and Al-Mhdawi	Transportation and Automotive (TRA and AUT)	7
Yücenur *et al.*, Bhardwaj, and Ma	Healthcare and Pharmaceutical (HEA and PHA)	4
Tripathi, Rustono *et al.*,	Environment and Renewable (ENV and REN)	4
Ayyildiz and Taskin, Belouaar and Kazar, Pouyakian *et al.*,	Consumer and E-Commerce (C'mer and E-CO)	3
Puppala and Manoharan, Radulescu and Radulescu, Ervural and Ayaz, Küçüktopçu *et al.*	Technology and AI integration (TEC and AI)	6
Sałabun, Zhu *et al.*, Samal and Dash, Chennoufi, Madanchain, Rani *et al.*, and Deveci *et al.*	Methodological and Cross-Industry (MET and CRO-IN)	12

Table 3: *The growing capabilities of hybrid FMEA methodologies.*

Trend	Description	Techniques/Models	Applications
Rise of Fuzzy Logic and Fuzzy Sets	Fuzzy logic became central to handling uncertainty in risk prioritization, replacing rigid RPN scoring.	Fuzzy TOPSIS, FAHP, IF-TOPSIS, Fermatean fuzzy sets, fuzzy clustering, fuzzy entropy	Oil and gas, urban planning, transportation, manufacturing, food safety, LNG storage
Integration of MCDM Techniques	Multicriteria Decision-Making (MCDM) methods were widely adopted to weigh and rank failure modes more effectively.	AHP, WASPAS, SWARA, VIKOR, MARCOS, MABAC, BWM, COCOSO	Renewable energy, e-waste recycling, construction, healthcare, EV procurement
COPRAS and PROMETHEE II	These ranking methods gained traction for their ability to handle complex decision matrices and trade-offs.	COPRAS, PROMETHEE II	IoT platform selection, pipeline safety, and environmental risk
Neuro-Fuzzy Systems	AI-enhanced fuzzy systems improved predictive accuracy and real-time diagnostics.	ANFIS, fuzzy expert systems, fuzzy cognitive maps	Automotive, welding, agriculture, LNG leak prediction, subsea compressors
Bayesian Networks	Probabilistic modeling helped capture dynamic risk evolution and interdependencies.	Dynamic Bayesian Networks, hybrid fuzzy-Bayesian models	Subsea systems, hydrogen storage, textile machinery, pipeline fault prediction
Fault Tree Analysis (FTA)	FTA was integrated with fuzzy and probabilistic models to enhance reliability forecasting.	FTA + Markov modeling, fuzzy-grey FMECA	Process industries, petrochemicals, safety-critical systems
Evolution of FMEA Itself	FMEA transformed from a static tool to a dynamic, AI-supported framework with hybrid weighting and logic systems.	Weighted RPN, fuzzy RPN, Software FMEA, RPM + HAZOP, fuzzy-GRA, fuzzy rough sets	Metro rail, aerospace, marine safety, smart manufacturing, blockchain mining
AI and Machine Learning Integration	AI models enabled adaptive risk evaluation and predictive maintenance.	ML algorithms, digital twins, real-time analytics	Supply chains, healthcare sterilization, crawler cranes, workplace safety
Sector-Specific Customization	Tailored FMEA models addressed unique risks in specialized domains.	q-ROFN QFD, fuzzy VIKOR, fuzzy Z-numbers, Bonferroni operators	Organ transplants, autonomous shipping, CO_2 emissions, PPE compliance, e-commerce ranking

The business world's view of risk has deeply changed. Hybrid FMEA has evolved from a simple technical tool into a more revolutionary strategy for managing industrial safety. Instead of just reacting to problems, companies are now using these intelligent systems to predict and prevent them. This shift is powered by a combination of Machine Learning, AI, fuzzy logic, and decision science, producing tools that are both incredibly precise and contextually aware. Customized for sectors ranging from healthcare to manufacturing, oil and gas to aerospace, these systems deliver highly accurate and relevant risk management. This is a definitive move away from a passive, reactive posture to a proactive one where organizations take control, using real-time data to build core resilience. Proactive preparation is no longer optional; it is essential.

The most cited authors in hybrid FMEA research (2020-2025)

The period from 2020 to 2025 marked significant growth in hybrid Failure Mode and Effects Analysis (FMEA) research. This era was defined by a major shift toward integrating artificial intelligence, fuzzy logic, multi-criteria decision-making (MCDM), and Industry 4.0 technologies into traditional reliability frameworks. Driven by a need for greater accuracy and adaptability in complex systems, the field experienced considerable methodological innovation.

Table 4 illustrates this academic expansion by stressing the most cited authors, whose work has been instrumental in shaping the domain. Their contributions have not only advanced the theoretical foundations of hybrid FMEA but have also provided actionable frameworks for risk assessment and failure prioritization in sectors like manufacturing, healthcare, and engineering. An analysis of these citation patterns reveals the key intellectual leaders whose scholarship continues to inspire and guide progress in this evolving field.

The journals with a central role in promoting or disseminating research on hybrid FMEA techniques
The growth in the adoption and applications of mixture strategies to Failure Mode and Effects Analysis (FMEA), allowing a set of integrated methods like fuzzy logic, Analytic Hierarchy Process (AHP), and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), etc, has gone a long way in promoting the application of the risk valuation across differs industrial fields. Within the period covered in this review, the use of bibliometric assessment has recognized some scholarly articles that have played a central role in sharing research that explores, refines, and uses these mixed or hybrid methods. The research of Xiao *et al.* (2023) and Meng *et al.* (2023) stood out in mapping the contributions of these prescribed journals, by not only revealing their intellectual outlines in the field, but also stressing the arenas within which the most powerful and creative developments were taken to the academic and expert world. Table 5 establishes that the journal with the highest impact has floated over the years in the publication of integrated/hybrid techniques of Failure Mode and Effects Analysis in risk valuation.

Table 4: *The top 20 most cited authors in the hybrid FMEA (2020–2025).*

Rank	Tittle	Journal	Author/Year	Hybrid Method	Citation
1	A hybrid MCDM-based FMEA model for identification of critical failure modes	Soft Computing	M. Yazdani, S. Zarandi 2020	MCDM, TOPSI, and DEMATEL	210
2	Fuzzy AHP–TOPSIS hybrid model for FMEA prioritization	Expert Systems with Applications	Tavakkoli-Moghaddam *et al.* 2021	Fuzzy Logic, AHP, TOPSIS	198
3	A Hybrid FMEA-ROC-CoCoSo Approach for Improved Risk Assessment	Algorithms	Vitor Anes, António Abreu 2024	FMEA, ROC, and CoCoSo	185
4	Hybrid FMEA using Bayesian networks and fuzzy logic	Reliability Engineering and System Safety	L. Liu, Y. Zhang 2022	FMEA, Fuzzy Logic, and Bayesian Networks (BN)	174
5	A hybrid integrated multi-criteria decision-making approach for risk assessment	International Journal of Quality and Reliability Management	Ammar Chakhrit *et al.* 2023	FMEA, AHP, PROMETHEE, and RDEA	162
6	Combining FMEA with Grey Relational Analysis for risk ranking	Applied Soft Computing	J. Wang, T. Chen 2020	FMEA and GRA	165

Table continues on next page..............

Rank	Tittle	Journal	Author/Year	Hybrid Method	Citation
7	Hybrid FMEA with machine learning for predictive risk analysis	IEEE Transactions on Industrial Informatics	A. Kumar, R. Singh 2023	FMEA and ML	153
8	Integrated FMEA–VIKOR method for risk prioritization	Safety Science	S. K. Ghosh, P. Roy 2021	FMEA and VIKOR	147
9	Rethinking FMEA for Today's Manufacturing Landscape	Journal of Failure Analysis and Prevention	Daniel Thomas 2025	AI, Machine Learning, IoT, and Experts' opinion,	139
10	Hybrid fuzzy DEMATEL-FMEA for healthcare risk assessment	Health Policy and Technology	Ghasemi, Hashemi, 2022	FMEA, Fuzzy Logic, and DEMATEL	132
11	Hybrid FMEA using entropy and PROMETHEE methods	Journal of Intelligent Manufacturing	R. Alizadeh, B. Kiani 2021	FMEA, Entropy Method, and PROMETHEE	121
12	A hybrid approach to FMEA using ANP and fuzzy logic	International Journal of Production Research	N. Singh, A. Sharma 2023	Fuzzy Logic, ANP, and Integration Process	118
13	Hybrid FMEA for criticality assessment in automotive industry	International Journal of Quality and Reliability Management	M. Bougofa *et al.* 2024	FAHP + Rough TOPSIS, AHP + PROMETHEE and Cost-Based FMEA + FAHP + EFMULTIMOORA	110
14	FMEA enhanced with hybrid decision trees and neural networks	Engineering Applications of Artificial Intelligence	T. Oliveira, M. Costa 2022	Decision Trees and Artificial Neural Networks (ANNs)	105
15	Hybrid FMEA for risk mitigation in supply chains	Journal of Manufacturing Systems	S. Patel, K. Mehta 2021	FMEA + AHP-PROMETHEE, FMEA + Fuzzy AHP, FMEA + MCDM, and FMEA + IoT Sensor Data	99
16	Hybrid fuzzy FMEA for construction safety assessment	Automation in Construction	A. Rahimi, H. Khosravi 2020	Fuzzy FMEA Core, Fuzzy DEMATEL, ANP, and Final Risk Prioritization	94
17	Hybrid FMEA with interval type-2 fuzzy sets	Information Sciences	B. Zhang, L. Huang 2023	IT2F-FMEA + Fuzzy Petri Nets, IT2F-FMEA + DEMATEL-MABAC, and IT2F-FMEA + ORESTE	88
18	Hybrid FMEA for risk prioritization in renewable energy systems	Renewable and Sustainable Energy Reviews	F. Ali, M. Khan 2022	FMEA + SWARA + VIKOR, FMEA + ROC + CoCoSo, and FMEA + SF-SWARA + SF-WASPAS	85
19	Hybrid FMEA using Dempster–Shafer theory and fuzzy logic	Knowledge-Based Systems	Y. Chen, Z. Li 2021	DST-Fuzzy FMEA, Fuzzy-D Numbers-Based FMEA, and Fuzzy Logic + DST	82
20	Hybrid FMEA for cybersecurity risk assessment	Computers and Security	J. Park, S. Lee 2024	FMEA + ROC + CoCoSo, Fuzzy AHP-FMEA, FMEA + Dempster–Shafer Theory and FMEA + CVSS Integration	79

The Industrial application

The chart above (Figure 2) paints a clear picture of how different industries are embracing Failure Modes and Effects Analysis (FMEA) and its integrated techniques. It offers valuable insight into how various sectors tackle risk, reliability, and quality management.

At the lead is the Oil and Gas/Energy sector (OG and E), accounting for 20% of FMEA activity. This robust indication echoes the industry's deep-rooted commitment to organised risk assessment, which is vital for guaranteeing safety, reliability, and compliance with demanding standards. Methodological and Cross-Industry Contributions (MET and CRO-IN) follow at a close range of 17%, displaying a growing adaptability to hybrid FMEA approaches that span multiple sectors. These indications show a proactive attitude toward managing risk and enhancing reliability.

Table 5: *Top 20 influential journals Publishers on Hybrid FMEA Techniques (2020–2025).*

Rank	Journal Name	Publisher	Focus Area
1	Reliability Engineering and System Safety	Elsevier	Reliability, safety, risk modeling
2	Expert Systems with Applications	Elsevier	AI, decision support, hybrid systems
3	IEEE Transactions on Engineering Management	IEEE	Engineering decision-making, risk analysis
4	Journal of Intelligent Manufacturing	Springer	Smart manufacturing, hybrid modeling
5	Applied Soft Computing	Elsevier	Fuzzy logic, hybrid optimization
6	Computers and Industrial Engineering	Elsevier	Industrial systems, hybrid MCDM
7	International Journal of Production Research	Taylor and Francis	Production systems, risk prioritization
8	Journal of Failure Analysis and Prevention	Springer	Failure analysis, hybrid FMEA applications
9	Safety Science	Elsevier	Risk management, safety systems
10	Engineering Failure Analysis	Elsevier	Case studies, hybrid diagnostics
11	International Journal of Industrial Engineering	Nova Science Publishers	Systems engineering, hybrid tools
12	Journal of Risk and Reliability	SAGE	Reliability modeling, hybrid FMEA
13	International Journal of Quality and Reliability Management	Emerald	Quality control, hybrid risk assessment
14	Design Science	Cambridge University Press	AI-driven FMEA, LLM integration
15	Systems	MDPI	Hybrid MCDM-FMEA frameworks
16	Journal of Manufacturing Systems	Elsevier	Process optimization, hybrid techniques
17	International Journal of Advanced Manufacturing Tech	Springer	Advanced FMEA, hybrid modeling
18	Journal of Mechanical Engineering Science	SAGE	Mechanical systems, hybrid diagnostics
19	International Journal of System Assurance Engineering	Springer	Assurance modeling, hybrid FMEA
20	Journal of Industrial Information Integration	Elsevier	AI, IoT, hybrid failure analysis

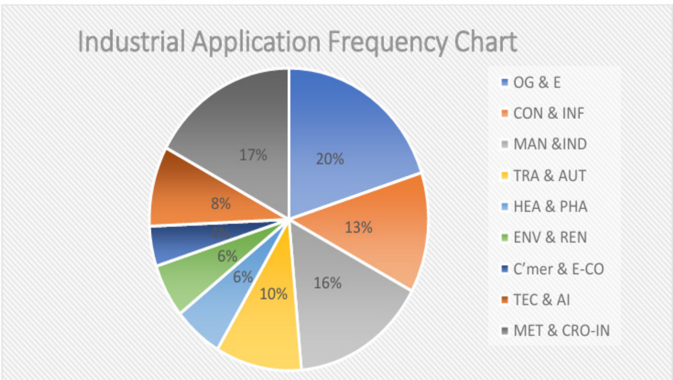

Figure 2: *Hybrid FMEA industrial application frequency chart.*

Discussion

Manufacturing (MAN and IND), this comes in at 16%, underlining the sector continued focus on systematic risk management. Next is Construction and Infrastructure (CON and INF), seen a notable uptick, accounting for 13%, with Transportation/ Automobile contributions coming on 10%. The usage of technology and AI applications is 8% of FMEA adoption, which indicates the growing importance of these tools in risk prediction modeling. Healthcare and Pharmaceuticals (HEA and PHA) and Environmental and Renewable Energy (ENV and REN) are making significant steps to introduce FMEA into their business, at 6% each. Closing the chart is the Food Industry, displayed by Consumer and E-Commerce (C'MER and E-CO), which completes the chart with 4%, representing the increasing consciousness of risk regulation in the consumer-related industries.

The data presented above reveal a strong correlation between an industry's risk exposure and its reliance on hybrid FMEA methodologies. These advanced techniques are most deeply adopted in sectors characterized by complex systems, stringent regulatory oversight, or critical safety concerns. As operational challenges continue to evolve, the role of FMEA is poised for further expansion. This growth will likely be driven by its integration with complementary tools that enhance its adaptability and efficiency, thereby enabling industries to proactively manage unpredictability.

The growth trends of Hybrid FMEA

The growth trend of hybrid FMEA application across the industry between 2020 and 2025 has indicated a positive drift, evolving from a static risk assessment tool into a dynamic, intelligent framework. This alteration or changes was driven by the integration of advanced technologies, particularly artificial intelligence, fuzzy logic, and decision science, enabling organizations to manage risks with greater precision and adaptability proactively. The key drifts and innovations include:

1. The use of Fuzzy Logic and Sets: Substituting rigid RPN scoring with nuanced uncertainty handling using tools like fuzzy TOPSIS, FAHP, and entropy models, as it is widely applied in oil and gas, manufacturing, and urban planning.
2. Application of Multicriteria Decision-Making (MCDM): Techniques like AHP, VIKOR, and SWARA contributed immensely to improving failure mode ranking across sectors like renewable energy and healthcare.
3. The Advanced Ranking Models: COPRAS and PROMETHEE II allowed complex trade-off analysis in IoT and environmental risk settings.
4. The use of Neuro-Fuzzy Systems: This is an AI-enhanced fuzzy model (e.g., ANFIS) that boosted predictive diagnostics in automotive and agriculture.
5. Bayesian Networks: Captured dynamic risk evolution and interdependencies in hydrogen storage and pipeline systems.
6. Fault Tree Analysis (FTA): Combined with fuzzy and probabilistic models for reliability forecasting in petrochemicals and safety-critical systems.
7. FMEA Evolution: Shifted to AI-supported, hybrid-weighted systems tailored for aerospace, smart manufacturing, and blockchain.
8. AI and Machine Learning: Enabled real-time analytics and predictive maintenance in supply chains and workplace safety.
9. Sector-Specific Customization: Tailored models addressed niche risks in organ transplants, autonomous shipping, and PPE compliance.

Organizations moved from reactive risk management to proactive, predictive systems. Hybrid FMEA became an approach shift, leveraging real-time data and intelligent tools to anticipate and mitigate risks before they materialize. This approach fostered resilience, relevance, and precision across diverse industries.

Citations and journals (Figure 3), where influence meets visibility: There's a clear pattern: Papers published in high-impact journals tend to attract more citations. For example, Soft Computing and Expert Systems with Applications top the list, hosting the two most-cited studies with 210 and 198 citations, respectively. Their broad readership and technical rigor make them ideal platforms for influential research. Other well-established journals like Reliability Engineering and System Safety (174 citations) and Applied Soft Computing (165 citations) also show strong performance, reinforcing the idea that visibility and credibility go hand in hand.

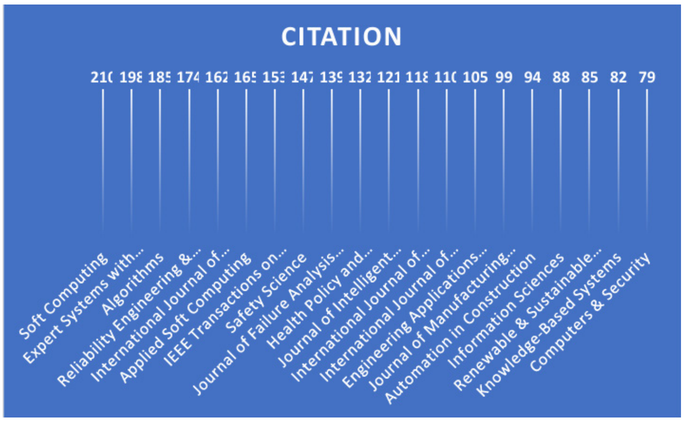

Figure 3: *Citations vs Journals*

Interestingly, newer or more niche journals are making waves too. Algorithms and the Journal of Failure Analysis and Prevention, despite being less mainstream, have garnered 185 and 139 citations. That's a strong signal that hybrid FMEA models are gaining traction across diverse academic communities.

Meanwhile, domain-specific journals such as Health Policy and Technology and Renewable and Sustainable Energy Reviews show moderate citation counts (132 and 85), suggesting that while their reach may be narrower, their relevance within specialized fields remains high.

(d) Citations and Authors (Figure 4) Knowledge combines with Novelty: In the scholarly scenery of hybrid FMEA, foundational knowledge and novel contributions remain paramount. M. Yazdani and S. Zarandi received the highest number of citations (210), underscoring the significant influence of their work in integrating Multi-Criteria Decision-Making

(MCDM) with FMEA. Following closely, H. Tavakkoli-Moghaddam and his collaborators secured the second position with 198 citations, a testament to their contributions in merging fuzzy logic with decision-making tools.

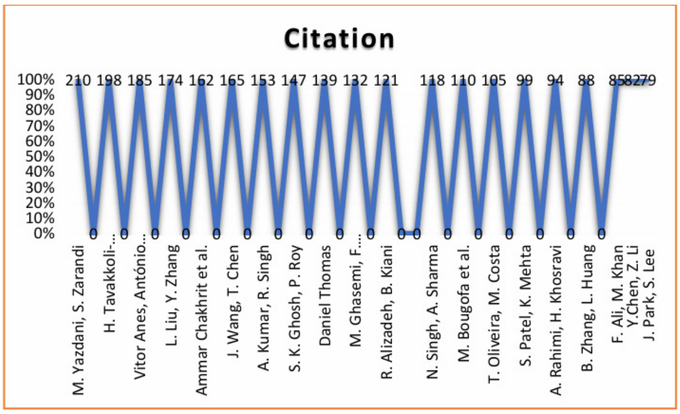

Figure 4: *Citations vs authors.*

Notably, the field is also witnessing the rapid emergence of influential new voices. A 2024 paper by Vitor Anes and Antonio Abreu has already accrued 185 citations, signaling a substantial and immediate impact, likely due to the innovative methodology they introduced.

In the same view, Liu and Zhang (174 citations) and Ammar Chakhrit and colleagues (162 citations) demonstrate the effectiveness of the methodology and their relevant issues, giving it an academic traction in a remarkably short period of time. Even the recent work by Daniel Thomas (2025) and Park and Lee (2024) is already gaining attention. Their consideration of AI, IoT, and cybersecurity shows that they are striving toward a more active, sophisticated, and technologically-driven risk assessment models. Finally, the current journals, together with experienced researchers, will continue to lead in the number of citations; however, the situation is growing. New methods and new areas like artificial intelligence, intelligent manufacturing, and renewable energy are changing the way FMEA is practiced and learned. The reference styles are a history of scholarly sophistication and technological relevance. Hybrid FMEA is no longer a meager tool of reliability, but it is emerging into a multi-disciplinary framework that is as flexible as the industries in which it is applied.

(e) Top Journals and Publishers in Hybrid FMEA Research (2020–2025): Academic studies and investigations in the field of hybrid Failure Mode and Effects Analysis (FMEA) have witnessed a surprising grip over the last five years and have found a home in a varied list of reputable journals as possible.

Elsevier is the leading publisher in this field, with 9 of the top 20 relevant journals. Key titles such as Reliability Engineering and System Safety, Expert Systems with Applications, and Applied Soft Computing have been instrumental in advancing traditional FMEA by disseminating research on AI-based models, fuzzy logic, and sophisticated decision-support systems.

Other major publishers, including IEEE, Springer, SAGE, and Taylor and Francis, have also contributed substantially. Their journals have explored the application of hybrid FMEA across diverse areas like engineering management, smart manufacturing, failure diagnostics, and quality assurance. This prolific publishing activity reflects a broader paradigm shift towards intelligent, data-driven risk assessment, where conventional reliability models are being enhanced or replaced by modern computational techniques.

Collectively, these publishers and their journals have been pivotal in cultivating an interdisciplinary domain of innovation. They have not only expanded the scope of FMEA but have also established a foundational knowledge base for future advancements in how industrial risk is perceived and managed.

Conclusion

In conclusion, the limitations of traditional FMEA, particularly in managing uncertainty, have prompted a significant shift toward integrated hybrid models. Analyzing literature from 2020 to 2025 reveals a clear paradigm shift in risk assessment, driven by the adoption of frameworks that combine Fuzzy Logic, Machine Learning, and Multi-criteria Decision-Making (MCDM), etc, to overcome the shortcomings of the Risk Priority Number (RPN). This trend points toward the development of more context-sensitive, flexible, and data-driven tools.

This review has categorized these advancements, noting the rise of precise methodologies like fuzzy FMEA, machine learning, and digital twins. The implementation of these sophisticated, combined approaches signifies a transformative improvement in risk management. The future of FMEA lies in these more competent, resilient, and adaptive systems, capable of navigating the increasing complexity of modern engineering and technology.

Acknowledgement

The authors would like to express their sincere gratitude to the Departments of Mechanical Engineering at the Federal University of Petroleum Resources, Effurun, Delta State, Nigeria, and the Federal University of Technology, Ikot Abasi, Akwa Ibom State, Nigeria, for their academic and institutional support.

Novelty Statement

This study presents a comprehensive literature review of recent (2020–2025) advancements in Failure Mode and Effects Analysis (FMEA), with a specific focus on hybrid and improved models incorporating Risk Priority Number (RPN) enhancements. Unlike previous reviews, this work systematically addresses key research gaps by evaluating industrial applicability, growth trends of integrated approaches, citation impact of authors and journals, and the dissemination channels of hybrid FMEA methodologies. The study provides a structured synthesis of emerging innovations and highlights future research directions for improving decision-making accuracy and risk prioritization in industrial systems.

Author's Contribution

Joseph J. Akpan: Conceptualization, methodology, formal analysis, writing original draft, and visualization.
Ikuobase Emovon: Methodology, formal analysis, data curation, review and editing, supervision.
Chinedum O Mgbemena: Validation, investigation, data curation, review and editing, supervision.
Modestus Okwu: Validation, investigation, visualization, review and editing, supervision.

Generative AI and AI assisted technology statement
The authors declare that no generative AI and AI assisted technology was used in the creation of this manuscript.

Conflict of interest
The authors have declared no conflict of interest.

References

Ahmed, S., Li, T., Huang, S., Cao, J. 2023. Dynamic and quantitative risk assessment of cruise ship pod propulsion system failure: An integrated Type-2 Fuzzy-Bayesian approach. Ocean Engineering, 279, Article 114601. https://doi.org/10.1016/j.oceaneng.2023.114601

Akbar, F., Zaki, S. (2023). Fixed-roof hydrocarbon oil storage tank: An approach to reliability engineering tools. Journal of Failure Analysis and Prevention, 23(5), 2044–2064. https://doi.org/10.1007/s11668-023-01733-5

Alazemi, F. K. A. O. H., Ariffin, M. K. A. B. M., Mustapha, F. B., Supeni, E. E. B. 2022. A new fuzzy TOPSIS-based machine learning framework for minimizing completion time in supply chains. International Journal of Fuzzy Systems, 24(3), 1669–1695. https://doi.org/10.1007/s40815-021-01226-3

Alber, S. 2016. A guide to failure analysis for the oil and gas industry. EWI.

Ali, S. I., Lal, B., Ahmad, F. 2024. Risk prioritization in a core preparation experiment using fuzzy VIKOR integrated with Shannon entropy method. Ain Shams Engineering Journal, 15(2), Article 102421. https://doi.org/10.1016/j.asej.2023.102421

Al-Mhdawi, M. K. S., Qazi, A., Dacre, N., Al-Emad, N., Buniya, M. K., Rahim, A. A. 2024. Implementation of a combined fuzzy controller model to enhance risk assessment in oil and gas construction projects. IEEE Access, 12, 68319–68333. https://doi.org/10.1109/ACCESS.2024.3399129

Altunhan, İ., Sakin, M., Kaya, Ü., Ak, M. F. 2023. Strategic framework for ANFIS and BIM use on risk management at natural gas pipeline project. In Digitalization in construction pp. 85–100. Springer. https://doi.org/10.1007/978-3-031-09753-9_8

Alvand, A., Mirhosseini, S. M., Ehsanifar, M., Zeighami, E., Mohammadi, A. 2021. Identification and assessment of risk in construction projects using the integrated FMEA-SWARA-WASPAS model under fuzzy environment: A case study of a construction project in Iran. International Journal of Construction Management, 23(3), 392–404. https://doi.org/10.1080/15623599.2021.1877875

Anes, V., Abreu, A. 2024. A hybrid FMEA-ROC-CoCoSo approach for improved risk assessment and reduced complexity in failure mode prioritization. Algorithms, 17(12), Article 585. https://doi.org/10.3390/a17120585

Aswin, K. R., Renjith, V. R., Akshay, K. R. 2022. FMECA using fuzzy logic and grey theory: A comparative case study applied to ammonia storage facility. International Journal of System Assurance Engineering and Management, 13(4), 2084–2103. https://doi.org/10.1007/s13198-022-01620-6

Ayağ, Z. 2021. A comparison study of fuzzy-based multiple-criteria decision-making methods to evaluating green concept alternatives in a new product development environment. International Journal of Intelligent Computing and Cybernetics, 14(3), 412–438. https://doi.org/10.1108/IJICC-03-2021-0040

Aydin, N., Seker, S., Şen, C. 2022. A new risk assessment framework for safety in oil and gas industry: Application of FMEA and BWM based picture fuzzy MABAC. Journal of Petroleum Science and Engineering, 219, Article 111059. https://doi.org/10.1016/j.petrol.2022.111059

Ayyildiz, E., Gumus, A. T. 2020. A novel spherical fuzzy AHP-integrated spherical WASPAS methodology for petrol station location selection problem: A real case study for İstanbul. Environmental Science and Pollution Research, 27(29), 36109–36120. https://doi.org/10.1007/s11356-020-09640-0

Beiranvand, B. 2024. Development of modified fuzzy FMEA method in environmental risk assessment of earth dams. Scientific Reports, 14, Article 17585. https://doi.org/10.1038/s41598-024-68217-w

Beldek, T., Konyalıoğlu, A. K., Camgöz-Akdağ, H. 2020. A fuzzy MCDM approach for project selection criteria prioritization in a big-four company: Evidences from Turkey consultancy sector. In Advances in Intelligent Systems and Computing (Vol. 1029, pp. 796–803). Springer. https://doi.org/10.1007/978-3-030-23756-1_95

Belouaar, H., Kazar, O., Zouai, M., Merizig, A. 2022. A new ranking approach for E-commerce websites based on fuzzy TOPSIS algorithm. Bulletin of Electrical Engineering and Informatics, 11(2), 936–946. https://doi.org/10.11591/eei.v11i2.3563

Bhardwaj, R., Mani, N., Singh, L., Sharma, A. 2024. A new score function for interval-valued intuitionistic fuzzy set and its application to MADM problems with partial weight information. In Strategic fuzzy extensions and decision-making techniques (pp. 25–36). CRC Press. https://doi.org/10.1201/9781003497219-4

Bhattacharjee, P., Dey, V., Mandal, U. K. 2020. Risk assessment by failure mode and effects analysis (FMEA) using an interval number based logistic regression model. Safety Science, 132, Article 104967. https://doi.org/10.1016/j.ssci.2020.104967

Bhol, S. G., Mohanty, J. R., Pattnaik, P. K. 2024. Enhancing cybersecurity metrics evaluation through the application of fuzzy AHP methodology. In Lecture Notes in Networks and Systems (Vol. 1010, pp. 135–147). Springer https://doi.org/10.1007/978-981-97-5412-0_10.

Bilgili, F., Zarali, F., Ilgün, M. F., Dumrul, C., Dumrul, Y. 2022. The evaluation of renewable energy alternatives for sustainable development in Turkey using intuitionistic fuzzy-TOPSIS method. Renewable Energy, 189, 1443–1456. https://www.sciencedirect.com/science/article/pii/S096014812200341X https://doi.org/10.1016/j.renene.2022.03.058

Biswas, A., Baranwal, G., Tripathi, A. K. 2022. ABAC: Alternative by alternative comparison based multi-criteria decision making method. Expert Systems with Applications, 208, Article 118174. https://doi.org/10.1016/j.eswa.2022.118174

Bongo, M. F., Inot, J. A., Sebios, C. 2020. Risk analysis on the current design of wooden-hulled boats with outrigger using fuzzy FMEA. International Journal of Productivity and Quality Management, 31(1), 134–152. https://doi.org/10.1504/IJPQM.2020.109334

Cardiel-Ortega, J. J., Baeza-Serrato, R. 2023. Failure mode and effect analysis with a fuzzy logic approach. Systems, 11(7), Article 348. https://doi.org/10.3390/systems11070348

Cardiel-Ortega, J. J., Baeza-Serrato, R. 2024. Probabilistic fuzzy system for evaluation and classification in failure mode and effect analysis. Processes, 12(6), Article 1197. https://doi.org/10.3390/pr12061197

Ceylan, B. O., Akyar, D. A., Celik, M. S. 2023. A novel FMEA approach for risk assessment of air pollution from ships. Marine Policy, 150, Article 105536. https://doi.org/10.1016/j.marpol.2023.105536

Chakhrit, A., Chennoufi, M., Bouksour, O., Beidouri, Z. (2024). A neuro-fuzzy risk prediction methodology in the automotive part industry [Preprint]. Research Square. https://doi.org/10.21203/rs.3.rs-4208702/v1

Chakhrit, A., Chennoufi, M., Bouksour, O., Beidouri, Z. 2024. A neuro-fuzzy risk prediction methodology in the automotive part industry. Operations Research Forum, 5(4), Article 87. https://doi.org/10.1007/s43069-024-00380-2

Chang, K. H., Chen, Y. J., Liao, C. C. 2024. A novel improved FMEA method using data envelopment analysis method and 2-tuple fuzzy linguistic model. Annals of Operations Research, 341(1), 485–507. https://doi.org/10.1007/s10479-024-05998-3

Chen, C., Liu, J., Wang, S. 2025. A new approach for failure mode and effect analysis based on Fermatean fuzzy Z-number weighted Muirhead mean operator. Engineering Applications of Artificial Intelligence, 143, Article 110080. https://doi.org/10.1016/j.engappai.2025.110080

Chen, L., Pan, W. 2021. Review fuzzy multi-criteria decision-making in construction management using a network approach. Applied Soft Computing, 102, Article 107103. https://www.sciencedirect.com/science/article/pii/S1568494621000260 https://doi.org/10.1016/j.asoc.2021.107103

Chennoufi, M., Chakhrit, A. 2024. An extended FMECA approach using new risk assessment and prioritization based approach. International Journal of Information Technology, 16(3), 1595–1604. https://doi.org/10.1007/s41870-023-01455-9

Chukwuka, O. J., Ren, J., Wang, J., Paraskevadakis, D. 2024. Managing risk in emergency supply chains–An empirical study. International Journal of Logistics Research and Applications. Advance online publication. https://doi.org/10.1080/13675567.2024.2359645

De Resende, B. A., Dedini, F. G., Eckert, J. J., Sigahi, T. F. A. C., Pinto, J. de S., Zuin, V. G. 2024. Proposal of a facilitating methodology for fuzzy FMEA implementation with application in process risk analysis in the aeronautical sector. International Journal of Quality and Reliability Management, 41(4), 1063–1088. https://doi.org/10.1108/IJQRM-07-2023-0237

Deveci, M., Erdogan, N., Cali, U., Stekli, J., Zhong, S. 2021. Type-2 neutrosophic number based multi-attributive border approximation area comparison (MABAC) approach for offshore wind farm site selection in USA. Engineering Applications of Artificial Intelligence, 103, Article 104307. https://www.sciencedirect.com/science/article/pii/S0952197621001597 https://doi.org/10.1016/j.engappai.2021.104311

Deveci, M., Gokasar, I., Pamucar, D., Coffman, D. M., Papadonikolaki, E., Kucuksari, S. 2023. Assessing alternatives of including social robots in urban transport using fuzzy trigonometric operators based decision-making model. Technological Forecasting and Social Change, 194, Article 122743. https://doi.org/10.1016/j.techfore.2023.122743

Durrani, O., Zeeshan, Q. 2023. An assessment of risks in oil and gas construction projects in Pakistan: A quantitative approach using failure modes and effects analysis. Journal of Engineering, Management and Systems Engineering, 2(3), 180–195. https://doi.org/10.56578/jemse020305

Ebadzadeh, F., Monavari, S. M., Jozi, S. A., Robati, M., Rahimi, R. 2023. An integrated of fuzzy-WASPAS and E-FMEA methods for environmental risk assessment: A case study of petrochemical industry, Iran. Environmental Science and Pollution Research, 30(14), 40315–40326. https://doi.org/10.1007/s11356-022-25088-w

Efe, B., Efe, Ö. F. 2021. Quality function deployment based failure mode and effect analysis approach for risk evaluation. Neural Computing and Applications, 33(16), 10159–10174. https://doi.org/10.1007/s00521-021-05778-1

Efe, B., Efe, Ö. F. 2023. Fine-Kinney method based on fuzzy logic for natural gas pipeline project risk assessment. Soft Computing, 27(22), 16465–16482. https://doi.org/10.1007/s00500-023-09108-6

El Haimer, S., Kaicer, M., En-Naaoui, A., Aguezzoul, A. 2022. Use of fuzzy FMEA for health risk assessment: A Moroccan case study. ResearchGate. https://www.researchgate.net/

publication/362327114

El Hassani, I., Masrour, T., Kourouma, N., Tavčar, J. 2025. AI-driven FMEA: Integration of large language models for faster and more accurate risk analysis. Design Science, 11, Article e7. https://doi.org/10.1017/dsj.2025.7

Ervural, B., Ayaz, H. I. 2023. A fully data-driven FMEA framework for risk assessment on manufacturing processes using a hybrid approach. Engineering Failure Analysis, 152, Article 107525. https://doi.org/10.1016/j.engfailanal.2023.107525

Fattahi, R., Tavakkoli-Moghaddam, R., Khalilzadeh, M., Shahsavari-Pour, N., Soltani, R. 2020. A novel FMEA model based on fuzzy multiple-criteria decision-making methods for risk assessment. Journal of Enterprise Information Management, 33*(5), 881–904. https://doi.org/10.1108/JEIM-09-2019-0282

Ge, H., Gao, H., Chen, N.-Z., Lin, Z. 2022. An enhanced failure mode effect analysis-based risk assessment for subsea compressor systems. Journal of Offshore Mechanics and Arctic Engineering, 144(2), Article 021801. https://doi.org/10.1115/1.4052548

Ghasemi, F., Babamiri, M., Pashootan, Z. 2022. A comprehensive method for the quantification of medication error probability based on fuzzy SLIM. PLoS ONE, 17(2), Article e0264303. https://doi.org/10.1371/journal.pone.0264303

Gupta, G., Ghasemian, H., Janvekar, A. A. 2021. A novel failure mode effect and criticality analysis (FMECA) using fuzzy rule-based method: A case study of industrial centrifugal pump. Engineering Failure Analysis, 123, Article 105305 https://doi.org/10.1016/j.engfailanal.2021.105305

Haddad, A. N., da Costa, B. B. F., de Andrade, L. S., Hammad, A., Soares, C. A. P. 2021. Application of Fuzzy-TOPSIS method in supporting supplier selection with focus on HSE criteria: A case study in the oil and gas industry. Infrastructures, 6(8), Article 105. https://doi.org/10.3390/infrastructures6080105

Häring, I. 2021. Failure modes and effects analysis. In Technical safety, reliability and resilience (pp. 101–126). Springer. https://doi.org/10.1007/978-981-33-4272-9_7

Hassan, S., Wang, J., Kontovas, C., Bashir, M. 2022. Modified FMEA hazard identification for cross-country petroleum pipeline using Fuzzy Rule Base and approximate reasoning. Journal of Loss Prevention in the Process Industries, 74, Article 104616. https://doi.org/10.1016/j.jlp.2021.104616

Hu, Z., Lin, J. 2022. An integrated multicriteria group decision making methodology for property concealment risk assessment under Z-number environment. Expert Systems with Applications, 205, Article 117369. https://doi.org/10.1016/j.eswa.2022.117369

Huang, J., You, J.-X., Liu, H.-C., Song, M.-S. 2020. Failure mode and effect analysis improvement: A systematic literature review and future research agenda. Reliability Engineering and System Safety, 199, Article 106885. https://www.sciencedirect.com/science/article/pii/S095183201930105X https://doi.org/10.1016/j.ress.2020.106885

Ivančan, J., Lisjak, D. 2021. New FMEA risks ranking approach utilizing four fuzzy logic systems. Machines, 9(11), Article 292. https://doi.org/10.3390/machines9110292

James, S., Renjith, V. R. 2025. Quantitative risk assessment and consequence analysis of liquefied natural gas storage facility. Process Integration and Optimization for Sustainability*. Advance online publication. https://doi.org/10.1007/s41660-025-00504-z

Jana, C., Mohamadghasemi, A., Pal, M., Martinez, L. 2023. An improvement to the interval type-2 fuzzy VIKOR method. Knowledge-Based Systems, 280, Article 111055. https://doi.org/10.1016/j.knosys.2023.111055

Kan, Z., Wei, Y., Zhao, T., Cao, J. 2024. Risk evaluation of submarine pipelines in FMEA by combination of gray relation projection and VIKOR method. Ocean Engineering, 302, Article 117695. https://doi.org/10.1016/j.oceaneng.2024.117695

Kolios, A. J., Umofia, A., Shafiee, M. 2017. Failure mode and effects analysis using a fuzzy-TOPSIS method: A case study of subsea control module. International Journal of Multicriteria Decision Making, 7(1), 29–53. https://doi.org/10.1504/IJMCDM.2017.085154

Koohathongsumrit, N., Meethom, W. 2021. An integrated approach of fuzzy risk assessment model and data envelopment analysis for route selection in multimodal transportation networks. Expert Systems with Applications, 171, Article 114342. https://doi.org/10.1016/j.

eswa.2020.114342
Küçüktopçu, E., Cemek, B., Simsek, H. 2023. Application of Mamdani fuzzy inference system in poultry weight estimation. Animals, 13(15), Article 2471. https://doi.org/10.3390/ani13152471
Kumar, R. 2025. A comprehensive review of MCDM methods, applications, and emerging trends. Decision Making Advances, 3(1), 185–199. https://doi.org/10.31181/dma31202569
Kumari, S., Ahmad, K., Khan, Z. A., Ahmad, S. 2023. Failure mode and effects analysis of common effluent treatment plants of humid sub-tropical regions using fuzzy based MCDM methods. Engineering Failure Analysis, 145, Article 107010. https://doi.org/10.1016/j.engfailanal.2022.107010
Lee, Y. C., Leite, F., Lieberknecht, K. 2023. Prioritizing selection criteria of distributed circular water systems: A fuzzy based multi-criteria decision-making approach. Journal of Cleaner Production, 428, Article 139330. https://www.sciencedirect.com/science/article/pii/S095965262302231X https://doi.org/10.1016/j.jclepro.2023.138073
Lestari, S., Septiyana, D., Yuniawati, W. 2021. Fuzzy FMEA application to identification risk in-process production of Toyota Hi-Ace wiring harness product. J@ti Undip: Jurnal Teknik Industri, 16(3), 153–160. https://doi.org/10.14710/jati.16.3.153-160
Li, A. 2024. Risk assessment of crane operation hazards using modified FMEA approach with Z-number and set pair analysis. Heliyon, 10(9), Article e28603. https://doi.org/10.1016/j.heliyon.2024.e28603
Li, X., Han, Z., Zhang, R., Abbassi, R., Chang, D.2020. An integrated methodology to manage risk factors of aging urban oil and gas pipelines. Journal of Loss Prevention in the Process Industries, 66, Article 104154. https://doi.org/10.1016/j.jlp.2020.104154
Lingras, S., Basu, A., Kolhar, A. M., Rumao, S. 2025. Enhancing software DFMEA processes through ISO 26262 (automotive functional safety) and ISO 21434 (automotive cybersecurity): Addressing RPN limitations with risk priority matrix and HAZOP integration. Iconic Research and Engineering Journals, 8(7), 263–272. https://www.irejournals.com/paper-details/1706925
Liou, J. J. H., Liu, P. C. Y., Lo, H.-W. 2020. A failure mode assessment model based on neutrosophic logic for switched-mode power supply risk analysis. Mathematics, 8(12), Article 2145. https://doi.org/10.3390/math8122145
Liu, J., Li, X., Zhang, Y., Wang, J., Chen, G. 2024. Failure risk assessment by multi-state dynamic Bayesian network based on interval type-2 fuzzy sets and leaky-weighted sum algorithm: A case study of crude oil pipelines. *Expert Systems with Applications, 250*, Article 123942. https://doi.org/10.1016/j.eswa.2024.123942
Liu, Y., Yang, Z., He, J., Li, G., Zhong, Y. 2023. A new approach to failure mode and effect analysis under linguistic Z-number: A case study of CNC tool holders. Engineering Failure Analysis, 154, Article 107688. https://doi.org/10.1016/j.engfailanal.2023.107688
Liu, Z., Zhao, Y., Liu, P. 2023. An integrated FMEA framework considering expert reliability for classification and its application in aircraft power supply system. Engineering Applications of Artificial Intelligence, 123, Article 106319. https://doi.org/10.1016/j.engappai.2023.106319
Lo, H. W., Shiue, W., Liou, J. J. H., Tzeng, G. H. 2020. A hybrid MCDM-based FMEA model for identification of critical failure modes in manufacturing. Soft Computing, 24(20), 15733–15745. https://doi.org/10.1007/s00500-020-04903-x
Lonfinmakin, O. O., Emovon, I., Samuel, D. O., Sada, S. O., Oke, S. A. 2023. Prediction of optimal mild steel weld parameters using the adaptive neuro fuzzy inference system (ANFIS) technique [Preprint]. Research Square. https://doi.org/10.21203/rs.3.rs-3529666/v1
Ma, Q., Li, H., Zhang, X. 2024. A method based on q-rung orthopair fuzzy cognitive map and TOPSIS method for failure mode and effect analysis considering risk causal relationships. Engineering Failure Analysis, 158, Article 107970. https://doi.org/10.1016/j.engfailanal.2024.107970
Ma, X., Sun, H., Qin, H., Wang, Y., Zheng, Y. 2024. A novel multi-attribute decision making method based on interval-valued fermatean fuzzy bonferroni mean operators. Journal of Intelligent and Fuzzy Systems, 46(2), 4325–4345. https://doi.org/10.3233/JIFS-235495
Maan, H. Y., Hamad, M. S. 2021. Integration of

the failure mode and effect analysis method with the fuzzy analytic hierarchy process to assess risks and determine the priority of failure mode. International Journal of Transformations in Business Management, 11(1). \[Volume/Issue/Page numbers missing - check original].

Madanchian, M., Taherdoost, H. 2023. Guide to the TOPSIS method for multi-criteria decision making. Sustainable Social Development, 1(1), 1-6. https://doi.org/10.54517/ssd.v1i1.2220

Mardani Shahri, M., Jahromi, A. E., Houshmand, M. 2021. Failure mode and effect analysis using an integrated approach of clustering and MCDM under pythagorean fuzzy environment. Journal of Loss Prevention in the Process Industries, 72, Article 104591. https://doi.org/10.1016/j.jlp.2021.104591

Marhavilas, P. K., Filippidis, M., Koulinas, G. K., Koulouriotis, D. E. 2022. Safety-assessment by hybridizing the MCDM/AHP and HAZOP-DMRA techniques through safety's level colored maps: Implementation in a petrochemical industry. Alexandria Engineering Journal, 61(9), 6959–6977. https://doi.org/10.1016/j.aej.2021.12.040

Meng, X., Lu, Y., Liu, J. 2023. A risk evaluation model of electric power cloud platform from the information perspective based on fuzzy type-2 VIKOR. Computers and Industrial Engineering, 184, Article 109616. https://doi.org/10.1016/j.cie.2023.109616

Mishra, A. R., Rani, P., Saeidi, P., Deveci, M., Alrasheedi, A. F. 2024. Fermatean fuzzy score function and distance measure-based group decision making framework for household waste recycling plant location selection. Scientific Reports, 14(1), Article 13963. https://doi.org/10.1038/s41598-024-78158-z

Mokhtarzadeh, M., Rodríguez-Echeverría, J., Semanjski, I., Gautama, S. 2024. Hybrid intelligence failure analysis for industry 4.0: A literature review and future prospective. Journal of Intelligent Manufacturing, 36(4), 2309–2334. https://doi.org/10.1007/s10845-024-02376-5

Oreko, B. U., Emovon, I., Oreko, I. 2021. Fuzzy-grey relational analysis applied to optimal maintenance strategy selection: The case of Egbin thermal power station, Nigeria. ResearchGate. https://www.researchgate.net/publication/366701586

Pang, N., Yin, Z., Xia, R., Wang, T., Lyu, K., Liu, X. 2020. A fuzzy Markov model for risk and reliability prediction of engineering systems: A case study of a subsea wellhead connector. Applied Sciences, 10(19), Article 6902. https://doi.org/10.3390/app10196902

Pantazopoulos, G., Tsinopoulos, G. 2005. Process failure modes and effects analysis (PFMEA): A structured approach for quality improvement in the metal forming industry. Journal of Failure Analysis and Prevention, 5(2), 5–10. https://doi.org/10.1361/15477020522933

Panyukov, D. I., Nenashev, M. V., Demoretskii, D. A., Kozlovskii, V. N. 2024. Improved FMEA assessment of the detection probability for failure modes or their causes. Russian Engineering Research, 44(1), 142–145. https://doi.org/10.3103/S1068798X24010295

Peeters, J. F. W., Basten, R. J. I., Tinga, T. 2018. Improving failure analysis efficiency by combining FTA and FMEA in a recursive manner. Reliability Engineering and System Safety, 172, 36–44. https://doi.org/10.1016/j.ress.2017.11.024

Petrovskiy, E. A., Buryukin, F. A., Bukhtiyarov, V. V., Savich, I. V., Gagina, M. V. 2015. The FMEA-risk analysis of oil and gas process facilities with hazard assessment based on fuzzy logic. Modern Applied Science, 9*(5), 25–35. https://doi.org/10.5539/mas.v9n5p25

Pouyakian, M., Khatabakhsh, A., Yazdi, M., Zarei, E. 2022. Optimizing the allocation of risk control measures using fuzzy MCDM approach: Review and application. In Studies in Fuzziness and Soft Computing (Vol. 414, pp. 53–89). Springer. https://doi.org/10.1007/978-3-030-93352-4_4

Puppala, N. S., Manoharan, R. 2024. Optimizing pool mining performance: A VIKOR-based model for identifying reputed miners in blockchain networks. Concurrency and Computation: Practice and Experience, 36(21), Article e8211. https://doi.org/10.1002/cpe.8211

Puspitasari, N. B., Yuwono, M. R. A. 2022. Integrating fuzzy logic and house risk method for operational risk management in automotive industry. IOP Conference Series: Earth and Environmental Science, 1098(1), Article 012007. https://doi.org/10.1088/1755-1315/1098/1/012007

Qaid, A. A. A., Ahmad, R., Mustafa, S. A., Mohammed, B. A. 2024. A systematic reliability-centred maintenance framework with fuzzy computational integration a case study of manufacturing process machinery. Journal of Quality in Maintenance Engineering, 30(2), 456–492. https://doi.org/10.1108/JQME-04-2022-0021

Qiao, W., Chen, Z., Hou, T. 2024. Failure mode and effects analysis of accessibility in frigid zone campus buildings. Sustainability, 16(8), Article 3437. https://doi.org/10.3390/su16083437

Rădulescu, C. Z., Rădulescu, M. 2024. A hybrid group multi-criteria approach based on SAW, TOPSIS, VIKOR, and COPRAS methods for complex IoT selection problems. Electronics, 13(4), Article 789. https://doi.org/10.3390/electronics13040789

Rani, P., Mishra, A. R. 2022. Interval-valued fermatean fuzzy sets with multi-criteria weighted aggregated sum product assessment-based decision analysis framework. Neural Computing and Applications, 34, 8051–8067. https://doi.org/10.1007/s00521-021-06782-1

Rasu, S. 2023. The role of DFMEA and PFMEA in ensuring product safety and reliability. ESP International Journal of Advancements in Computational Technology, 1(2), 126–130. https://doi.org/10.56472/25838628/IJACT-V1I2P113

Razzaq, A., Junaid, A., Akhtar, R., Ullah, S., Khan, M. 2024. Failure mode and effects analysis of suction hose manufacturing industry: A case study of automobiles. International Journal on Interactive Design and Manufacturing, 18(9), 6809–6824. https://doi.org/10.1007/s12008-024-01849-4

Relkar, A. S. 2021. Risk analysis of equipment failure through failure mode and effect analysis and fault tree analysis. Journal of Failure Analysis and Prevention, 21(3), 793–805. https://doi.org/10.1007/s11668-021-01117-7

Rong, Y., Yu, L., Liu, Y., Simic, V., Garg, H. 2024. The FMEA model based on LOPCOW-ARAS methods with interval-valued Fermatean fuzzy information for risk assessment of RandD projects in industrial robot offline programming systems. Computational and Applied Mathematics, 43(1), Article 1. https://doi.org/10.1007/s40314-023-02532-2

Rustono, R., Triasrini, F. M., Paniya, P. 2023. Failure mode and effect analysis on risk management at an oil and gas survey company in Indonesia. International Journal of Science, Technology and Management, 4(6), 1725–1732. https://doi.org/10.46729/ijstm.v4i6.988

Sabripoor, A., Azar, A., Moghaddam, A. S. 2024. Risk assessment of organ transplant operation: A fuzzy hybrid MCDM approach based on fuzzy FMEA. PLoS ONE, 19(5), Article e0299655. https://doi.org/10.1371/journal.pone.0299655

Sagnak, M., Kazancoglu, Y., Ozen, Y. D. O., Garza-Reyes, J. A. 2020. Decision-making for risk evaluation: Integration of prospect theory with failure modes and effects analysis (FMEA). International Journal of Quality and Reliability Management, 37(6–7), 939–956. https://doi.org/10.1108/IJQRM-01-2020-0013

Sałabun, W., Watróbski, J., Shekhovtsov, A. 2020. Are MCDA methods benchmarkable? A comparative study of TOPSIS, VIKOR, COPRAS, and PROMETHEE II methods. Symmetry, 12(9), Article 1549. https://doi.org/10.3390/sym12091549

Samal, S., Dash, R. 2022. An empirical comparison of TOPSIS and VIKOR for ranking decision-making models. In Smart Innovation, Systems and Technologies (Vol. 286, pp. 429–437). Springer. https://doi.org/10.1007/978-981-16-9873-6_39

Samir, Deyab, M., John's Newfoundland, S. 2017. Failure modeling and analysis of offshore process components, Conference presentation.

Sarafraz, P., Jahangiri, M., Faghihi, M. A., Ghaem, H., Parsarad, S., Rismanchian, M., Sadeghian, M. 2023. Safety, health, and environmental risk assessment of the aromatic outlet of Imam Khomeini Petrochemical Company using LOPA and fuzzy-LOPA and pollutants and control actions using the Bow-tie method. Frontiers in Public Health, 11, Article 1251548 https://doi.org/10.3389/fpubh.2023.1251548.

Sari, E. B. 2021. Fuzzy based failure mode and effect analysis towards to risks of autonomous maintenance activities: As a TPM implementation. Ege Academic Review, 21(1), 17–27. https://doi.org/10.21121/eab.873999

Sarkar, D., Singh, M. 2022. Risk analysis by integrated fuzzy expected value method and fuzzy failure mode and effect analysis for an elevated metro rail project of Ahmedabad, India. International Journal of Construction

Management, 22(10), 1818–1829. https://doi.org/10.1080/15623599.2020.1742634

Shafiee, M., Animah, I. 2022. An integrated FMEA and MCDA based risk management approach to support life extension of subsea facilities in high-pressure–high-temperature (HPHT) conditions. Journal of Marine Engineering and Technology, 21(4), 189–204. https://doi.org/10.1080/20464177.2020.1827486

Shamsuzzoha, A., Piya, S., Shamsuzzaman, M. 2021. Application of fuzzy TOPSIS framework for selecting complex project in a case company. Journal of Global Operations and Strategic Sourcing, 14(3), 528–566. https://doi.org/10.1108/JGOSS-07-2020-0040

Shao, J., Zhong, S., Tian, M., Liu, Y. 2024. Combining fuzzy MCDM with Kano model and FMEA: A novel 3-phase MCDM method for reliable assessment. Annals of Operations Research, 342(1), 725–765. https://doi.org/10.1007/s10479-024-05878-w

Şimşek, B., İç, Y. T. 2020. Fuzzy failure mode and effect analysis application to reduce risk level in a ready-mixed concrete plant: A fuzzy rule based system modelling approach. Mathematics and Computers in Simulation, 178, 549–587. https://doi.org/10.1016/j.matcom.2020.06.024

Stoumpos, S., Theotokatos, G. 2022. A novel methodology for marine dual fuel engines sensors diagnostics and health management. International Journal of Engine Research, 23(6), 974–994. https://doi.org/10.1177/1468087421998635

Subramanian, R., Taterh, S., Singh, D., Lee, H.-N. 2022. Efficient fine tuned trapezoidal fuzzy-based model for failure mode effect analysis risk prioritization. IEEE Access, 10, 50037–50046. https://doi.org/10.1109/ACCESS.2022.3172513

Tang, Y., Sun, Z., Zhou, D., Huang, Y. 2024. Failure mode and effects analysis using an improved pignistic probability transformation function and grey relational projection method. Complex and Intelligent Systems, 10(2), 2233–2247. https://doi.org/10.1007/s40747-023-01268-0

Tang, Y., Tan, S., Zhou, Y., Huang, Y., Zhou, D. 2023, May. An improved risk priority number model for FMEA based on belief measure. In 2023 35th Chinese Control and Decision Conference (CCDC) (pp. 3940–3945). IEEE. https://doi.org/10.1109/CCDC58219.2023.10326506

Tao, H., Jia, P., Wang, X., Wang, L. 2024. Reliability analysis of subsea control module based on dynamic Bayesian network and digital twin. Reliability Engineering and System Safety, 248, Article 110153. https://doi.org/10.1016/j.ress.2024.110153

Tavakkoli-Moghaddam, R. 2021. Risk assessment by a new FMEA model based on an extended AHP method under a fuzzy environment. Environmental Energy and Engineering Research, 3(1), 61-76.

Thomas, D. 2025. Rethinking FMEA for today's manufacturing landscape considering innovation in risk analysis. Journal of Failure Analysis and Prevention, 25(1), 1–3. https://doi.org/10.1007/s11668-025-02092-z

Tian, Y., Song, S., Bao, S., Zhou, D., Wei, C. 2024. Canonical triangular interval type-2 fuzzy linguistic distribution assessment EDAS approach with its application to production supplier evaluation and ranking. Applied Soft Computing, 154, Article 111309. https://doi.org/10.1016/j.asoc.2024.111309

Tong, W. C. 2022. Fuzzy logic and decision-making: A paradigm shift in risk management. International Journal of Educational Science and Research Review, 9(2).

Tripathi, V. K., Singh, A., Patil, A. J., Sood, Y. R. 2021. An innovative fuzzy modelling technique for photovoltaic power generation farm's failure modes and effects analysis. In Intelligent computing techniques for smart energy systems (pp. 361–377). Springer. https://doi.org/10.1007/978-981-33-4412-9_22

Turgay, S. 2024. Optimizing failure modes and effects analysis with fuzzy multiattribute grey theory and DEA. Design, Construction, Maintenance, 4, 7–18. https://doi.org/10.37394/232022.2024.4.2

Ungvári, E., Gyurika, I. G., Csiszér, T. 2023. Evaluation of the failure effects of a screwing station using a new approached FMEA. MethodsX, 11, Article 102278. https://doi.org/10.1016/j.mex.2023.102278

Wang, C., Liu, Y., Hou, W., Wang, G., Zheng, Y. 2020. Reliability and availability modeling of Subsea Xmas tree system using Dynamic Bayesian network with different maintenance methods. Journal of Loss Prevention in the Process Industries, 64, Article 104066. https://doi.org/10.1016/j.jlp.2020.104066

Wang, T., Li, H., Qian, Y., Huang, B., Zhou, X. 2022. A regret-based three-way decision model under interval type-2 fuzzy environment. IEEE Transactions on Fuzzy Systems, 30(1), 175–189. https://doi.org/10.1109/TFUZZ.2020.3033448.

Xiao, W.-S., Liu, C., Li, G.-X., Liu, J. 2023. Reliability analysis of subsea control system using FMEA and FFTA [Preprint]. Research Square. https://doi.org/10.21203/rs.3.rs-2984143/v1

Xiao, Z., Wang, J., Sun, Y. 2024. Risk assessment of emergency operations of floating storage and regasification unit. Journal of Marine Engineering and Technology, 23(5), 357–372. https://doi.org/10.1080/20464177.2024.2364994

Yang, X., Wang, J., Loughney, S., Yang, Z., Zhao, F. 2024. Integrating software FMEA and STPA to develop a Bayesian network-based software risk model for autonomous ships. Journal of Marine Science and Engineering, 12(1), Article 4. https://doi.org/10.3390/jmse12010004

Yener, Y., Can, G. F. 2021. A FMEA based novel intuitionistic fuzzy approach proposal: Intuitionistic fuzzy advance MCDM and mathematical modeling integration. Expert Systems with Applications, 183, Article 115413. https://doi.org/10.1016/j.eswa.2021.115413

Yu, J., Wu, Y., Li, C., Wang, B. 2024. Risk assessment of liquefied natural gas storage tank leakage using failure mode and effects analysis with Fermatean fuzzy sets and CoCoSo method. Applied Soft Computing, 154, Article 111334. https://doi.org/10.1016/j.asoc.2024.111334

Yuan, G., Li, S., Zhang, L., Wang, H. 2024. Study on quantitative evaluation method for failure risk factors of the high-temperature and high-pressure downhole safety valve. Sustainability, 16(5), Article 1896. https://doi.org/10.3390/su16051896

Yücenur, G. N., Atay, İ., Argon, S., Gül, E. F. 2019. Integrating fuzzy prioritization method and FMEA in the operational processes of an automotive company. International Journal of Knowledge-Based Organizations, 9(3), 14–32. https://doi.org/10.4018/IJKBO.2019070102

Zhu, Y., Wang, X., Chen, W., Guo, H., Li, D. 2022. A variable weight-based interval type-2 fuzzy rough comprehensive evaluation method for curtain grouting efficiency assessment. Neural Computing and Applications, 34(10), 7851–7879. https://doi.org/10.1007/s00521-021-06864-0