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A New Hybrid FMECA Model for Prioritizing Failure Modes Using Multi-Criteria Decision Making

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Abstract

This paper is an extension of the conference publication (Kahouadji & Belkaid, 2022). It introduces a new Hybrid Failure Modes, effects, and criticality analysis (FMECA) Model for Prioritizing Failure Modes using Multi-Criteria Decision-Making (MCDM) technique which can serve as a substitute for the conventional risk priority number (RPN) methodology. Our argument is that the RPN method has inherent limitations when it comes to evaluating risks and pinpointing crucial concerns, which can lead to imprecise risk management decisions. The proposed hybrid FMECA combines the strengths of subjective assessments, such as expert judgment and descriptive data, with objective, measurable data such as numerical scores. This integration provides a more comprehensive evaluation of risks and criticality. The hybrid approach incorporates the French repairability index (RI) as a new factor which enhances accuracy and reliability while strengthen the eco-awareness of the risk assessment. We integrate two MCDM (VIKOR & TOPSIS) methods into the hybrid FMECA approach and illustrate its effectiveness through a case study where we identify and prioritize critical issues in a complex system. The results of the study confirm that the hybrid FMECA approach provides a more robust risk management tool compared to the traditional RPN method, making it a valuable technique for engineers and risk managers.

Keywords

FMECA; RPN; MCDM; TOPSIS; VIKOR; repairability index.

Introduction

Manufacturers must continually adjust their production, logistics, and maintenance methods to satisfy customer demands in an increasingly competitive economic climate. To meet production standards and deadlines, they must maintain and repair their equipment, so machines remain operational and available. This necessitates implementing procedures to enhance equipment maintainability and minimize the likehood breakdowns.

The process of increasing equipment maintainability involves a variety of tasks that manufacturers must undertake to ensure optimal functionality and availability of their equipment. These activities include routine inspection and testing of machinery components, equipment cleaning and lubrication, parts replacement, and system upgrades or modifications. Additionally, manufacturers must train their maintenance teams on the latest techniques and technologies to ensure they have the necessary skills to identify and fix equipment issues promptly.

Alongside maintenance activities, manufacturers should prioritize to carrying out Preventive Maintenance (PM) tasks as a means to reduce the likelihood of equipment breakdowns. PM was first introduced in the 1950s as a way to prevent failures (Murthy et al., 2002) instead of relying solely on Corrective Maintenance (CM). PM involves performing maintenance activities based on a set schedule or predetermined criteria, aimed at identifying or preventing the deterioration of functionality in a structure, system, or component, to extend lifespan.

By adopting these preventive measures, decision makers can reduce downtime and production losses caused by equipment failures, ultimately improving their bottom line and maintaining a competitive edge in the market. This strategy helps to decrease the requirement for expansive repairs and downtimes and improve overall efficiency.

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PM can be performed by in-house maintenance staff or by a third-party contractor. In either case, it is important to have a well-designed and well-executed preventive maintenance program in place. The program should be flexible, allowing for adjustments to be made as equipment, facilities, and systems evolve, and should be based on best practices and industry standards.

Predictive Maintenance (PdM) represents a more advanced approach to maintenance compared to PM and often involves the use of condition-monitoring systems. Within the framework of PdM, the analysis of repetitive or high-risk failures is conducted by studying historical data related to a machine's operational failures. Subsequently, maintenance tasks are executed while the machine is operational, guided by the condition of the monitored component (Basri et al., 2017). One of the most widely used methods in the field of PdM is Failure Mode and Effects Analysis (FMEA) / FMECA. This technique involves analyzing systems, designs, processes, or services to proactively identify and mitigate known or potential failures, problems, errors, and other issues, preventing their adverse impact on the customer (Stamatis, 2023).

In the context of FMECA, Severity (Se), Occurrence (Oc), and Detection (De) are three parameters assessed to prioritize potential failure modes (PFMs). "Se" focuses on the impact and consequences of failure modes on system performance, reliability, safety and potential harm caused by failures. "Oc" relates to the likelihood or frequency of failure modes occurring within a system. "De" evaluates the ability to identify or detect failure modes before they lead to severe consequences.

It can be observed that FMECA primarily focuses on the internal characteristics and behavior of a system, its components, and their interactions. It aims to enhance system reliability, safety, and performance but does not explicitly incorporate considerations related to environmental protection and sustainability.

To address this gap, we introduce the RI as a new criterion to minimize environmental impact while assessing failure modes in the FMECA process. In our approach, the user or the service provider evaluates the RI of the products.

Also, in order to prioritize failure modes, RPN is determined by multiplying Se, Oc, and De. Each criterion is typically assigned a rating on a scale, such as 1 to 10, with higher values indicating more severe, frequent, or difficult-to-detect failure modes: $RPN = Se * Oc * De$.

It is important to note that the RPN is a quantitative ranking derived from subjective ratings assigned by individuals involved in the analysis. Decision makers may assign different ratings based on their expertise, experience, or biases. Therefore, the RPN should be used as a guide rather than an absolute measure of risk and it should be supplemented with expert judgment and engineering knowledge to make informed decisions in the context of FMECA.

The RPN method has faced numerous criticisms, including its lack of a scientific basis in calculations. To address this deficiency, we will apply in this paper two MCDMs namely VIKOR and TOPSIS in order to enhance the decision-making quality and assist managers in prioritizing various failure modes.

Literature review of FMEA/FMECA

The aerospace industry pioneered the formal design methodology known as (FMEA) during the 1960s (Bowles et al., 1995). The systematic and proactive approach aims to identify and analyze PFMs within a system, product, or process while evaluating the associated risks. This methodology involves identifying PFMs, assessing their impact, and determining their likelihood of Oc. The analysis results serve as a basis for prioritizing risk reduction efforts and enhancing system reliability. To rank failure modes according to their criticality, a procedure known as Criticality Analysis (CA) is often utilized in conjunction with FMEA. The combination of these two techniques is commonly referred to as FMECA (Bouti & Kadi, 1994). It takes into account the criticality of a failure mode in addition to its likelihood of Oc and impact. The criticality of a failure mode is determined based on the Se of the consequences and the probability of the failure mode occurring. The FMECA methodology is commonly used in industries such as aerospace and defense, where the reliability and safety of systems is of utmost importance.

In recent years, FMECA has emerged as one of the most extensively utilized methods for identifying critical failure modes. In 1999, the International Organization for Standardization (ISO) published the initial version of standard ISO12132, offering guidelines for preparing a Design FMEA specifically for thin-walled half bearings used in machinery. A newer version of the standard was subsequently released in 2017, encompassing updated guidelines and a comprehensive list of common PFMs, effects, and causes. The numerical assessment of risks based on Se, Oc and De factors may vary depending on the specific application, manufacturer, and customer, necessitating a case-by-case evaluation. The current ISO standard does not furnish numerical data for risk evaluation, as it must be determined independently for each individual scenario.

In the past five years, numerous studies utilizing FMECA have been published, including the work by

(Singh et al., 2019). In this study, FMECA was employed to identify preventive measures aimed at mitigating the risk of transformer failure in the future. The measures included addressing the root causes of failure, reducing both the Se and likelihood of Oc, and implementing additional strategies to minimize overall risk. In (Renjith et al., 2018) the authors utilized a fuzzy RPN (FRPN) method to overcome limitations of FMECA, particularly concerns regarding the accuracy of the mathematical formula used to calculate RPN. Additional studies have focused on risk prioritization using different approaches, such as the study referenced in (Carpitella & Certa, 2018) where the authors proposed a fuzzy TOPSIS method for ranking failure modes identified in the FMECA process. This approach combines reliability analyses and multi-criteria decision methods to optimize maintenance activities for complex systems.

Recent applications of MCDM in FMECA

The objective of Multi-Criteria Decision-Making techniques is to evaluate different options considering multiple criteria and conflicting goals. These methods have proven be highly efficient when it comes to analyzing, assessing, and prioritizing decision-making projects (Voogd, 1982).

MCDM methods offer numerous benefits that enable decision makers to:

- Define evaluation criteria
- Generate and evaluate various alternatives to achieve contradictory objectives
- Analyze solutions using both qualitative and quantitative criteria
- Adjust problem configurations with agility

Table 1 summarizes the latest integrations of MCDM methods in FMECA.

To gain a deeper understanding of the application of MCDM techniques in the context of FMECA, we recommend focusing on two papers (Dabous et al., 2021a; Dabous et al., 2021b), which extensively review the integration of these two techniques together in the manufacturing industry. These papers specifically explore prominent engineering sectors such as aerospace, energy, infrastructure and marine industries. In the review analysis, a total of sixty-seven peer-reviewed journal articles published from 2010 to 2019 were examined. The findings reveal that the electronics manufacturing sector exhibits the highest number of applications. Additionally, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) emerges as the most commonly utilized MCDM approach within the manufacturing industry. The primary objective of these papers is to assist researchers in enhancing their understanding of MCDM-based FMECA in the manufacturing industry. The papers also explore the trends and limitations of MCDM-based FMECA across different industries, identify areas requiring further research, and propose potential directions for future studies. The review further establishes that the energy industry represents the most prevalent application domain, while the utilization of evidence theory emerges as the dominant MCDM approach.

Based on the literature review above, it can be noticed that MCDM methods integrated with FMECA are used in many fields, including engineering, project management, finance, logistics, quality, health, environment. These methods are frequently integrated with FMECA to enhance the decision-making process by considering multiple criteria such as Se, Oc and De of failure modes.

Even though the traditional FMECA approach is recognized for its numerous advantages, earlier researchers have criticized its limitations, including the formula used to calculate the RPN.

Moreover, the previously mentioned articles often showcase enhancements to FMECA by considering new parameters related to economic, social or environmental aspects such as maintenance cost, operator safety or environmental impact of failure modes.

Furthermore, applying various MCDM methods is necessary to address the lack of a scientific basis in RPN calculation.

In conclusion, to perform a comprehensive failure analysis of a system or equipment using the FMEA method, it is necessary to hybridize it either by adding new parameters alongside Se, Oc and De or by employing MCDM techniques to enhance the quality of decision-making for managers.

Motivations and Contribution

In this paper, we adopt the same philosophy as the cited studies above, by incorporating the RI as a new factor in risk assessment step of FMECA. This addition helps decision-makers identify failure modes that may have negative environmental consequences and help organizations make more informed decisions that balance safety and environmental concerns. Additionally, we apply MCDM methods such as TOPSIS and VIKOR to support organizations in making better decisions. These methods provide a structured and transparent approach for comparing and prioritizing

Table 1
Latest integrations of MCDM methods in FMECA

MCDM	Used Criteria in FMECA process	Author(s) / Year	Contribution	Field of application
Fuzzy WASPAS	1. Latest integrations of MCDM methods in FMECA • Se • Oc • De • Extent of contamination.	Ebadzadeh, F. et al. (2023)	Evaluation of environmental risks in ammonia and urea production highlights CO2 emissions from the disposal tower as the most significant concern, requiring immediate attention. Prioritization of environmental aspects ranks these emissions highest among 24 identified factors, emphasizing their critical impact. Recommendation of mitigation measures aims to address these risks and reduce their environmental consequences.	Ammonia and urea production in the petrochemical industry
TODIM TOPSIS	• Se • Oc • De	Huang, J. et al. (2022)	Enhancement of the RPN method in FMEA addresses its limitations by integrating probabilistic linguistic term sets. This new strategy tackles uncertainty in risk assessments to establish a priority ranking for failure modes.	Theoretical study
EDAS BWM	• Se • Oc • De • Costs of non-production	Di Nardo, M. et al. (2022)	Creation of a novel methodology, EN-B-ED Dynamic FMECA, introduces the incorporation of the cost factor as an unknown variable. This enables the derivation of an objective weighted factor and risk index in the event of machine failure.	Agri-food sector
AHP TOPSIS	• Se • Oc • De	Djenadic, S. et al. (2022)	Use of fuzzy logic improves the risk evaluation method for engineering systems, overcoming the limitations of the traditional RPN approach.	Bucket-wheel excavators
TOPSIS VIKOR	• Se • Oc • De	Kahouadji, H. & Belkaid, F. (2022)	Implementation of an effective resolution strategy in FMECA focuses on the common use of an aggregating function to measure the “closeness to the ideal.	Industrial Robot Mitsubishi RV-2AJ in Festo Didactic Learning System for Automation
BWM PROMETHE ETOPSIS VIKOR EDAS	• Using Risk Expected Value (REV) instead of Se, Oc & De	Bhattacharjee, P. et al. (2022)	Introduction of a novel approach, the REV method aims to improve FMEA in identifying potential failures in product or process design. The individual influence and priority weights of PFMs are evaluated using subjective weights of risk factors, determined through Interval number-based and Multiple techniques.	Components of submersible pumps used in a power plant

Table 1 continued on the next page

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MCDM	Used Criteria in FMECA process	Author(s) / Year	Contribution	Field of application
COPRAS	• Se • Oc • De • Pollution range • Cost	(Rahnamay Bonab, S., & Osgooei, E. (2022)	Proposition of a new approach prioritizes environmental failures using the FMEA method, addressing the shortcomings of traditional FMEA by assigning weights to risk factors and considering uncertainty. This approach was compared to other common methods through sensitivity analysis, with results demonstrating that it is more reliable and effective in identifying high-risk failures.	Iranian wastewater treatment plant
ELECTRE TRI DEMATEL	• Se • Oc • De	(Ahmed, U. et al. (2021)	Identification of factors contributing to the emergence of additional failures in specific risk categories is crucial for promoting efficient maintenance practices, ultimately enhancing the overall performance of the analyzed system throughout its lifespan.	Vehicle deputed to provide street cleaning services
MAIRCAS MAIRCOS TOPSIS	• De • Oc • Se (Economic Severity, Social Severity, Environmental Severity)	(Boral, S. et al. (2021)	Use of Interval type-2 fuzzy sets minimizes linguistic uncertainties when evaluating failure modes in relation to risk factors. To depict the cause-and-effect connections between risk factors and determine their weights, an enhanced variant of the IT2F-DEMATEL method has been developed, specifically designed for group decision-making situations.	Process plant gearbox
PROMETHEE AHP TOPSIS	• Se • Oc • De	(Jafarpisheh, R. et al. (2021)	Development of a hybrid approach implements reliability-centered maintenance for mining transportation machines within a limestone complex. In addition, a novel FMECA approach integrates effective techniques under a q-rung orthopair fuzzy environment, enabling flexible and free expression of opinions. This approach also includes a comprehensive criteria weighting determination method.	Transportation systems in the mining industry
TODIM PROMETHEE II	• Se • Oc • De	(Liu, Z. et al. (2021)	Introduction of a novel FMECA approach integrates two techniques under a q-rung orthopair fuzzy environment, enabling flexible and free expression of opinions. This approach also includes a comprehensive criteria weighting determination method and a novel distance measurement for q-ROFSs.	Blood transfusion
Fuzzy ANP TOPSIS	• Economic • Environnemental • Social	(Pourmehdi, M. et al. (2021)	Provision of insights aims to improve the performance of collection centers in a reverse logistics context, with a focus on sustainability.	Steel manufacturing

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MCDM	Used Criteria in FMECA process	Author(s) / Year	Contribution	Field of application
Fuzzy TOPSIS	• Se • Oc • De	(Mzougui, I. & El Felsoufi, Z. (2020)	Improvement to FMEA is made by incorporating MCDM methods and the Design Structure Matrix method. This method is used to identify interactions between failures, enhancing the analysis.	Product under development.
TOPSIS	• Se • Oc • De	(Başhan, V. et al. (2020)	Exploration of FMEA and single-valued neutrosophic considers twenty-three primary risks commonly encountered in ship navigation. Through this analysis, significant risks such as extreme weather conditions and loss of maneuverability were identified. A corrective-preventive action plan is proposed, along with managerial implications for ship navigation based on these identified risks.	Ship navigation
DEMATEL TOPSIS	• Se • Oc • De • Expected costs • Environmental protection	(Lo, H. W. et al. (2020)	Enhancement of the overall assessment comprehensiveness is achieved by incorporating anticipated costs and environmental protection indicators into the FMEA model. Additionally, a decision-making trial and evaluation laboratory is utilized to further refine the assessment.	Machine tool manufacturing company
AHP ERVD	• Oc • De • Se is divided in two types of subfactors: – Safety, Health & Environment – Operational Severity	(Gugaliya, A. (2019)	Improvement of FMECA is achieved by decoupling severity into various factors that affect it. A hybrid MCDM approach is developed to enhance the effectiveness of FMECA.	Induction motors in a process plant
GRA TOPSIS	• Se • Oc • De	(Hu, Y. P. et al (2019)	Improvement of the imprecise evaluation of risks aims to address concerns with RPN in traditional FMEA methods. This approach utilizes two-dimensional uncertain linguistic variables and applies an effective method to establish risk rankings. A maximizing deviation method is also used to calculate the optimal weights of risk factors.	Healthcare risk analysis case

*The initials used in the table above are summarized in Table A, appendix section.

different alternatives leading to more effective risk management strategies that balance multiple criteria and incorporate diverse stakeholder perspectives.

In summary, the proposed model is novel in concept. Contributions of this paper are summarized below.

- This work extends the research conducted by Kahouadji and Belkaid (2022) by incorporating the RI as a key factor in the FMECA model.
- A comprehensive set of linguistic terms for evaluating the RI of each Failure Mode in the FMECA method are proposed.
- Two MCDM methods are implemented to enhance result robustness and reduce reliance on a single method that may lack reliability.
- The effectiveness of the proposed hybrid FMECA approach is demonstrated through a case study.

The advantages of the proposed approach are summarized below.

- The RI encourages resource conservation and extends product lifespan.
- The proposed strategy ensures a comprehensive evaluation, enhances result credibility and is applicable to risk management across various fields.
- Integrating the RI into the FMECA establishes a framework that promotes sustainability and environmental awareness.

We have selected the TOPSIS and VIKOR methods due to their distinct advantages. The VIKOR method ranks alternatives based on their closeness to the ideal solution, while the TOPSIS method prioritizes the alternative with the shortest distance to the ideal solution and the farthest distance from the negative-ideal solution.

Numerous MCDM methods have been developed to address real-world manufacturing challenges, including TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) and VIKOR, which translates to Multicriteria Optimization and Compromise Solution. To the best of our knowledge, several studies have applied either TOPSIS or VIKOR in the context of preventive and predictive maintenance (Babashamsi et al., 2016; Chundi et al., 2022; Özcan et al., 2017; Seiti & Hafezalkotob, 2019; Singh et al, 2016).

The French Repairability index (RI)

The French repairability index, also known as "Indice de Réparabilité" (RI), was introduced on January 1st, 2021. This index aims to inform consumers about the repairability of various consumer products, including electronic devices, appliances, and more. The RI rates products on a scale of 1 to 10, with a higher score indicating greater ease of repair. This rating system promotes repairability and sustainability by encouraging manufacturers to design more repairable products and helping consumers make informed purchasing decisions.

The rating system is based on predefined criteria established by French law, which consider factors such as the availability of spare parts, ease of disassembly, access to repair documentation, and software repairability. Currently, the index applies to select product categories, with plans for expansion in the future.

As anticipated, consumer advocates and environmental groups have welcomed this initiative, recognizing it as a positive step towards promoting sustainability and reducing electronic waste. France became the first country in the world to implement such a rating system, and other countries are considering similar policies. This initiative aligns with France's broader commitment to promote a circular economy, where products are designed to be reused, repaired, and recycled, rather than being disposed of after limited use.

The RI has already impacted the market, prompting some manufacturers to modify their designs to improve repairability and achieve a higher score on the index. The index has also increased consumer awareness of the importance of repairability and sustainability in product design. By informing consumers about product repairability, the RI empowers them to make more informed choices and encourages manufacturers to prioritize sustainability and repairability in their designs.

Calculation method for the index

Calculation of the RI for each product model is based on the five criteria below:

- Documentation: score determined by the manufacturer's commitment to make technical documents available, free of charge for a number of years, to repairers and consumers.
- Ease of disassembly and access, tools and fasteners: score determined by the ease of disassembly of the product, the type of tools required, and the characteristics of the fixings.
- Availability of spare parts: score determined by the manufacturer's commitment to the availability duration of spare parts and the delivery time.
- Spare parts price: score determined by the ratio between the selling price of spare parts and the price of the product.
- Specifics: the score is established based on sub-criteria specific to the product category.

The RI is calculated based on these criterion scores, which is then converted into a rating out of 10. The details of the rating, presented in the table below (Tab. 2), must be made available to the consumer by the seller at the time of purchase and, if different, by the manufacturer upon request, for each concerned model.

Finally, the RI enables producers, importers, distributors, or other market players of electrical and electronic equipment to inform consumers about a product's repairability. The brand's commitment lies in the transparency of the information (Fig. 1). It allows the performance of products to be translated in terms of cost savings for both retailers and end customers.

Fig. 1. Examples of RI displayed on products

Table 2
Criteria of the repairability index

Criteria		**Sub-criteria**		**Sub-criteria grade**	**Weight of sub-criteria**	**Criteria grade**	**Total of criteria grades**
Documentation	$\mathbf{C_1^{RI}}$	Availability duration of technical documentation, including usage and maintenance information.	$\mathbf{C_{11}^{RI}}$	…/10	2	… /20	**…/100**
Ease of disassembly and access, tools, fasteners	$\mathbf{C_2^{RI}}$	Ease of disassembly of parts in List 2*	$\mathbf{C_{21}^{RI}}$	…/10	1	… /20	
		Necessary tools (List 2)	$\mathbf{C_{22}^{RI}}$	…/10	0,5		
		Characteristics of the fastenings between the parts in List 1** and List 2*	$\mathbf{C_{23}^{RI}}$	…/10	0,5		
Availability of spare parts	$\mathbf{C_3^{RI}}$	Availability period of parts in list 2	$\mathbf{C_{31}^{RI}}$	…/10	1	… /20	
		Availability period of parts in list 1	$\mathbf{C_{32}^{RI}}$	…/10	0,5		
		Delivery time of parts in list 2	$\mathbf{C_{33}^{RI}}$	…/10	0,3		
		Delivery time of parts in list 1	$\mathbf{C_{43}^{RI}}$	…/10	0,2		
Spare parts price	$\mathbf{C_4^{RI}}$	Price ratio of parts in list 2 to the price of new equipment	$\mathbf{C_{41}^{RI}}$	…/10	2	… /20	
Specifics	$\mathbf{C_5^{RI}}$		$\mathbf{C_{51}^{RI}}$	…/10	1	… /20	
			$\mathbf{C_{52}^{RI}}$	…/10	0,5		
			$\mathbf{C_{53}^{RI}}$	… /10	0,5		
		Repairability Index grade					**…/10**

**List 2: list of the top 3 to 5 spare parts (depending on the equipment category) whose breakage or failure is most common.*
***List 1: list of the top 10 other spare parts (depending on the equipment category) whose good condition is necessary for the equipment to function properly.*

Case study

To validate the effectiveness of the proposed TOPSIS/VIKOR-FMECA model, a benchmark case study was conducted using data from the Festo Didactic Learning System for Automation at the Manufacturing Engineering Laboratory of Tlemcen. This educational system offers practical training projects that encompass planning, assembly, programming, maintenance, and fault diagnosis, enabling hands-on learning through real world project phases.

For the case study, a team consisting of two professional technicians and two professors from the University of Tlemcen applied the FMECA method using the robot station of the system for their training projects. The specific focus was on the Mitsubishi MELFA RV-2AJ robot model, which is a jointed arm robot featuring five anthropomorphic articulate degrees of freedom (DOF). The robot's effector is located at the top of the arm, and each joint has one rotational degree of freedom around its respective axis (Ayob et al., 2014). Fig. 2 illustrates the robot's design.

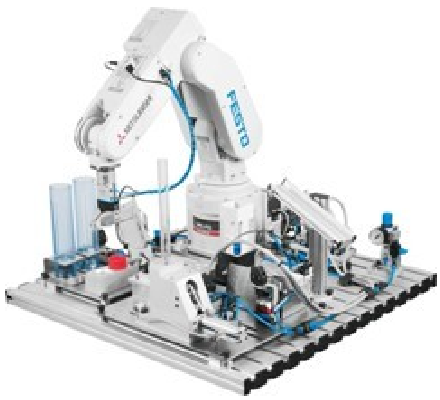

Fig. 2. Mitsubishi MELFA RV-2AJ

Proposed resolution process

The proposed model consists of three distinct phases (Fig. 3). In the initial phase, the FMECA method is implemented by a team of four members to identify potential failures, evaluate their effects, and assess factors such as Se, likelihood of Oc, De, and RI. Subsequently, (RPN) is computed, with a higher RPN indicating a higher priority for preventive action or resolution of the corresponding failure mode.

In the second phase, two MCDM methods, TOPSIS and VIKOR, are employed to rank the identified failure modes. These methods help to determine of the relative importance and priority of each failure mode.

In the final phase, the rankings derived from the RPN, TOPSIS, and VIKOR are compared to identify the most critical failure modes. This comparison highlights the failure modes that require immediate attention and preventive measures.

We selected these two approaches because they employ an aggregating function that represents the degree "closeness to the ideal solution". The VIKOR technique includes a ranking index based on a specific "closeness

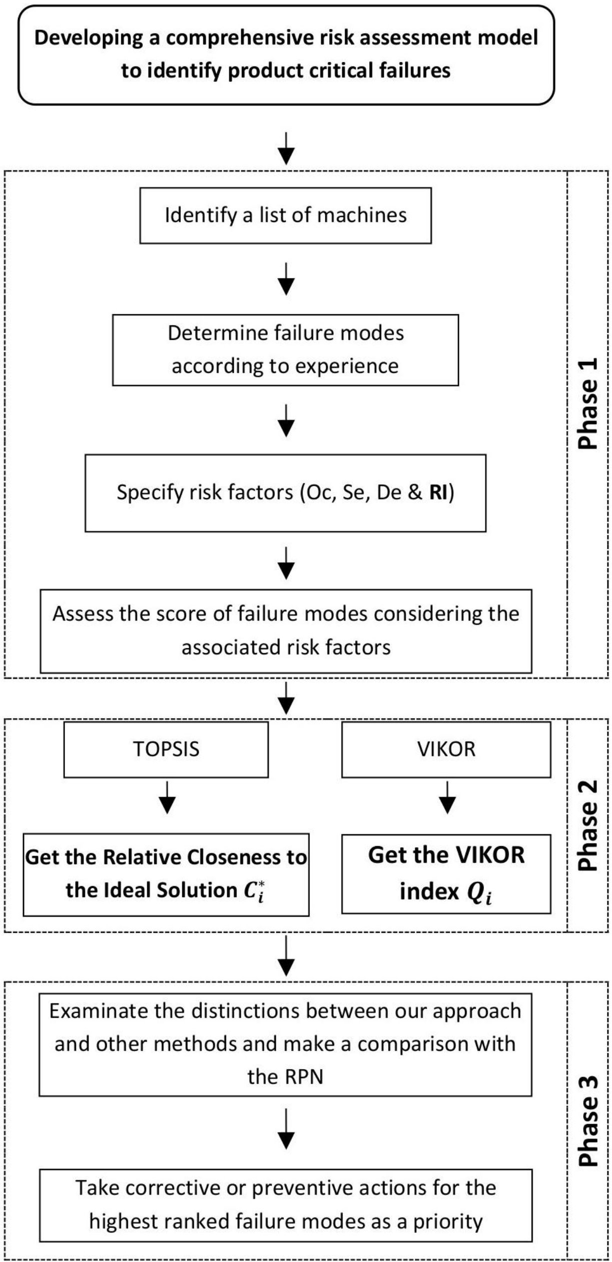

Fig. 3. Proposed TOPSIS/VIKOR-based FMECA Model FMECA deployment

to the ideal solution". On the other hand, the TOPSIS method operates on the principle that the selected alternative should have the "shortest distance to the ideal solution" and the "farthest distance from the negative-ideal solution". (Opricovic & Tzeng, 2004).

Phase 1

The FMECA team identified 12 possible failure modes for the Mitsubishi RV-2AJ Robot, as shown in Table 3.

Table 3
Failure modes identified for the Mitsubishi robot

FM $_i$	***Failure Modes***
FM_1	Loose bolts/screws on (robot installation/cover/hand/robot arm)
FM_2	Insecure connection of the power supply cable
FM_3	Insecure connection of the machine cable between the robot and the controller
FM_4	Cracks, foreign contaminants, or obstacles on the robot and controller cover
FM_5	Air leaks in the pneumatic system
FM_6	Clogging or hose damage in the pneumatic system's drain
FM_7	Unusual noise when the power is turned ON
FM_8	Deviation of the movement points from the X, Y, or Z axis
FM_9	Wear damage of cables
FM_{10}	Abnormal tension in the timing belt.
FM_{11}	Severe friction at the timing belt teeth
FM_{12}	Station shutdown

Table 4 presents the linguistic terms and their corresponding values assigned to Se, Oc, and De.

The following Tables (5, 6, 7 & 8) summarize the linguistic terms of RI.

As observed in Table 2, RI measures the repairability of products, rather than their failure modes. In this study, we use the RI criteria (Such as documentation, availability of spare parts, ease of disassembly, etc.) as a basis for defining linguistic terms, adapting it to evaluate the repairability of a failure mode in an FMECA analysis. This approach enables us to assess the repairability of each failure mode in an FMEA analysis.

Table 4
Failure modes identified for the Mitsubishi

(Se)	**(Oc)**	**(De)**	**Value**
No effect, no danger	No documented failures on similar products/processes	Fault is certain to be caught by testing	1
Very minor – usually noticed only by discriminating or very observant users	Low – relatively few failures	Fault almost certain to be caught by testing	2
Minor – only minor part of the system affected; noticed by average users	Moderate – some occasional failures	High probability that tests will catch fault	3
Moderate – most users are inconvenienced and/or annoyed	High – repeated failures	Moderate probability that tests will catch fault	4-6
High – loss of primary function; users are dissatisfied	Very high – failure is almost certain	Low probability that tests will catch fault	7-8
Very high – hazardous. Product becomes inoperative, customers angered	Very high – hazardous, where the product becomes inoperative, leading to customer dissatisfaction. The failure also possesses the potential to cause injury or even loss of life.	Fault will be passed undetected to user/customer	9-10

Table 5
Linguistic terms and values for documentation in RI

a) Documentation	
1.1) Duration of availability of technical documentation and information on usage and maintenance advice	**Value**
Non-existent: No technical documentation or information on usage and maintenance advice is available.	1
Very short: Technical documentation and maintenance information are available for a very short period of time	2
Short: Technical documentation and maintenance information are available for a limited period of time.	3
Moderate: Technical documentation and maintenance information are available for a moderate period of time.	4-6
Long: Technical documentation and maintenance information are available for an extended period of time.	7-8
Permanent: Technical documentation and maintenance information are available for the entire lifespan of the product.	10

Table 6
Linguistic terms and values for ease of disassembly and access, tools, fasteners in RI

b) Ease of disassembly and access, tools, fasteners			
2.1) Ease of disassembly of parts in List 2*	**2.2) Necessary tools (List 2)**	**2.3) Characteristics of the fastenings between the parts in List 1** and List 2**	**Value**
Very Difficult – Parts are extremely difficult to disassemble and may require specialized tools or expertise.	Inadequate: No tools or insufficient tools are available to complete the task at hand.	Undefined: There are no characteristics or information available regarding the fastenings between the parts in List 1 and List 2.	1
Difficult – Parts are challenging to disassemble and may require significant effort or skill.	Limited: A few basic tools are available, but they are not sufficient for efficient or effective work.	Basic: There are only a few basic characteristics known about the fastenings between the parts in List 1 and List 2.	2
Somewhat Difficult – Some parts may be challenging to disassemble, but most are relatively straightforward.	Basic: The necessary tools are available but may not be of the highest quality or be up to date.	General: The fastenings between the parts in List 1 and List 2 have some general characteristics that are known, but not in detail.	3
Neutral – Parts are neither difficult nor easy to disassemble.	Adequate: Sufficient tools are available to complete the task effectively, but there is room for improvement.	Known: Several characteristics of the fastenings between the parts in List 1 and List 2 that are known and can be described.	4–6
Easy – Disassembling parts is a straightforward and uncomplicated process.	Advanced: A range of high-quality tools is available, allowing for advanced techniques and approaches.	Defined: The characteristics of the fastenings between the parts in List 1 and List 2 are clearly defined and understood.	7–8
Very Easy – Parts can be disassembled with minimal effort and without the need for specialized tools or expertise.	Sophisticated: The available tools are specialized and advanced, allowing for complex work and in-depth analysis.	Detailed: The fastenings between the parts in List 1 and List 2 have detailed characteristics that can be studied and analyzed.	9–10

Table 7
Linguistic terms and values for availability of spare parts in RI

c) Availability of spare parts				
3.1) Availability period of parts in list 2	**3.2) Availability period of parts in list 1**	**3.3) Delivery time of parts in list 2**	**3,4) Delivery time of parts in list 1**	**Value**
None: The parts are not available.	None: The parts are not available.	Extended: The parts may take an extended period of time to be delivered, typically over a year.	Extended: The parts may take an extended period of time to be delivered, typically over a year.	1
Very short: The parts are only available for a very short period of time, making it difficult to obtain them.	Very short: The parts are only available for a very short period of time, making it difficult to obtain them.	Long: The parts may take a relatively long time to be delivered, typically several months to a year.	Long: The parts may take a relatively long time to be delivered, typically several months to a year.	2
Limited: The parts are available for a limited period of time, but may become difficult to find as time goes on.	Limited: The parts are available for a limited period of time, but may become difficult to find as time goes on.	Average: The parts can be delivered within an average time frame, typically within a few months without additional delays.	Average: The parts can be delivered within an average time frame, typically within a few months without additional delays.	3
Moderate: The parts are available for a moderate period of time and can be obtained relatively easily during this period.	Moderate: The parts are available for a moderate period of time and can be obtained relatively easily during this period.	Moderate: The parts can be delivered within a standard time frame, typically within a few weeks to a month.	Moderate: The parts can be delivered within a standard time frame, typically within a few weeks to a month.	4–6
Average: The parts are available for an average period of time and can be obtained without difficulty during this period.	Average: The parts are available for an average period of time and can be obtained without difficulty during this period.	Fast: The parts can be delivered within a reasonably fast time frame, typically within a week or two.	Fast: The parts can be delivered within a reasonably fast time frame, typically within a week or two.	7–8
Very long: The parts are available for a very long period of time, making them easy to find even decades after they were first produced.	Very long: The parts are available for a very long period of time, making them easy to find even decades after they were first produced.	Urgent: The parts can be delivered within a short period of time, typically within a day or two.	Urgent: The parts can be delivered within a short period of time, typically within a day or two.	9–10

Table 8
Linguistic terms and values for Spare parts price in RI

d) Spare parts price	
4.1) Price ratio of parts in list 2 to the price of new equipment	**Value**
Extreme: The price of parts is extremely high compared to the price of new equipment.	1
High: The price of parts is very high compared to the price of new equipment.	2
Average: The price of parts is similar to the price of new equipment.	3
Modest: The price of parts is moderately lower compared to the price of new equipment.	4–6
Significant: The price of parts is noticeably lower compared to the price of new equipment.	7–8
Negligible: The price of parts is insignificant compared to the price of new equipment.	9–10

Table 9
Numerical example of RI assessment

Failure Mode	**Criteria**	**Sub-criteria**	**Sub-criteria grade**	**Weight of sub-criteria**	**Criteria grade**	**Total of criteria grades**
FM_8 Backup battery dead	C_1^{RI}	C_{11}^{RI}	10/10	2	20/20	**70 /100**
	C_2^{RI}	C_{21}^{RI}	6 /10	1	12/20	
		C_{22}^{RI}	8 /10	0.5		
		C_{23}^{RI}	4 /10	0.5		
	C_3^{RI}	C_{31}^{RI}	3/10	1	6/20	
		C_{32}^{RI}	3/10	0.5		
		C_{33}^{RI}	3/10	0.3		
		C_{43}^{RI}	3/10	0.2		
	C_4^{RI}	C_{41}^{RI}	9/10	2	18/20	
	C_5^{RI}	C_{51}^{RI}	6/10	1	14/20	
		C_{52}^{RI}	9/10	0.5		
		C_{53}^{RI}	7/10	0.5		
	Repairability Index grade					**7.0 /10**

**List 2: list of the top 3 to 5 spare parts whose breakage or failure is most common in the considered failure mode*
***List 1: list of the top 10 other spare parts whose good condition is necessary for the equipment to function properly.*

In the following we present a numerical example of RI assessment.

Remark: This example considers a single failure mode (FM8 in this case). It should be noted that in order to adapt the same philosophy of the RI to an FMECA approach, the following modifications had to be made compared to table 1 of the RI evaluation:

- List 2, which concerns parts whose failure is very common, has been replaced by a list of parts that may represent the common cause of a failure mode;
- Specific criteria such as the skills of maintenance engineers or technicians (C_{51}^{RI}), duration of maintenance (C_{52}^{RI}) and risk of injury while fixing the failure mode (C_{53}^{RI}) have been added as subcriteria of criterion (C_5^{RI}) to make the RI assessment more robust.

Table 10 presents the risk assessment of failure modes based on Se, Oc, De, and RI.

Table 10
Assessment matrix

FMi	**(Se)**	**(Oc)**	**(De)**	**(RI)**
FM_1	7.50	2.5	6.25	8.00
FM_2	6.25	5.00	1.25	8.20
FM_3	6.25	5.00	1.25	8.00
FM_4	8.75	1.25	1.25	9.50
FM_5	8.75	1.25	1.25	6.30
FM_6	8.75	1.25	1.25	6.00
FM_7	5.00	8.75	1.25	5.90
FM_8	6.25	7.50	1.25	7.00
FM_9	7.50	1.25	5.00	5.80
FM_{10}	8.75	1.25	1.25	7.00
FM_{11}	1.25	1.25	1.00	7.00
FM_{12}	2.50	1.25	1.00	6.90

Phase 2

1. TOPSIS

TOPSIS is an MCDM method used to evaluate and rank alternatives based on multiple criteria. The method was introduced by Hwang and Yoon in 1981 (Hwang et al., 1981) and has since become a widely used decision-making tool.

This method, as the name suggests, is centered on identifying an ideal and an anti-ideal solution, and then measuring the distance between each alternative and these solutions. It is a well-known MCDM technique that has garnered significant interest and attention from researchers and scholars. It involves identifying a set of alternatives and evaluating them based on multiple criteria, such as cost, performance, quality, and risk, among others. The criteria are assigned weights to reflect their relative importance, and the alternatives are scored based on their performance on each criterion. The alternatives are then ranked based on their proximity to the ideal solution, which is the alternative with the best score on all criteria. In the following section, we will explain the sequence of steps involved in this technique.

Step 1: *Constructing the decision matrix of the given problem*

The decision matrix displays the relative performance of different alternatives in relation to multiple criteria:

$$[x_{ij}]_{mxn} = \begin{bmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}. \tag{1}$$

Step 2: *Construct the normalized decision matrix*

Each performance value of an alternative on a criterion is computed relative to the other alternative performances on that criterion as follows:

$$x^*_{ij} = \frac{x_{ij}}{\sqrt{\sum\limits_{i=1}^{m} x^2_{ij}}}, \tag{2}$$

where: $i = 1,\dots,m$ and $j = 1,\dots,n$, x^*_{ij} is a dimensionless number between [0,1] representing the normalized performance of the i^{th} alternative on the j^{th} criterion.

Step 3: *Computation of the weighted normalized decision matrix*

The third step involves multiplying the normalized decision matrix by the corresponding weight assigned to each criterion. The calculation of the weighted normalized values is performed in the following manner.

$$v_{ij} = w_j x^*_{ij}, \quad i = 1,\dots,m \text{ and } j = 1,\dots,n, \tag{3}$$

where: w_j is the weight of the j^{th} criterion and

$$\sum_{j=1}^{n} w_j = 1, \quad j = 1,\dots,n. \tag{4}$$

Step 4: *Determination of the ideal (Zenith) and anti-ideal (Nadir) solutions*

In the simplest scenario, the decision maker fixes the ideal and anti-ideal points. However, this approach should be avoided since it assumes that the decision maker can accurately determine these points, which introduce subjectivity to the process. An alternative approach is to consider the ideal solution (A^*) as:

$$\begin{aligned} A^* = &\{v^*_1, v^*_2, \dots, v^*_n\} = \\ &\{((v_{ij})|i \in I'), ((v_{ij})\,|i \in I'')\}, \\ &i = 1,\dots,m, \quad j = 1,\dots,n. \end{aligned} \tag{5}$$

The ideal solution is obtained by identifying the alternatives with the highest performance in the normalized decision matrix. Likewise, the anti-ideal solution (A^-) is

$$\begin{aligned} A^- = &\left\{v^-_1, v^-_2, \dots, v^-_n\right\} = \\ &\left\{\left((v_{ij})|i \in I'\right), ((v_{ij})|i \in I'')\right\}, \\ &i = 1,\dots,m, \quad j = 1,\dots,n. \end{aligned} \tag{6}$$

In this case, following the ideal solution, the anti-ideal solution is obtained by considering the worst performances in the normalized decision matrix. The ideal solution, denoted as I', corresponds to benefit criteria, while the anti-ideal solution, denoted as I'', corresponds to cost criteria. Another option, among several alternatives found in the literature, is to utilize absolute ideal and anti-ideal points. For example.

$$A^* = (1, 1, \dots, 1) \text{ and } A^- = (0, 0, \dots, 0). \tag{7}$$

Step 5: *Calculation of the separation measures*

This step involves calculating the distances of each alternative from the ideal solution, which can be expressed as follows:

$$\begin{aligned} D^*_i = &\sqrt{\sum_{j=1}^{n} \left(v_{ij} - v^*_j\right)^2}, \\ &i = 1,\dots,m, \quad j = 1,2,\dots,n. \end{aligned} \tag{8}$$

Similarly, the distances from the anti-ideal solution are calculated as follows:

$$\begin{aligned} D^-_i = &\sqrt{\sum_{j=1}^{n} \left(v_{ij} - v^-_j\right)^2}, \\ &i = 1,\dots,m, \quad j = 1,2,\dots,n. \end{aligned} \tag{9}$$

Step 6: *Determining the relative closeness to the ideal solution*

The relative closeness C_i^* is a value that always falls between 0 and 1, where an alternative is considered superior when its closeness value approaches 1. This value is calculated for each alternative and defined as follows:

$$C_i^* = \frac{D_i^-}{D_i^* + D_i^-}, \quad i = 1, \ldots, m. \tag{10}$$

Step 7: *Rank the order of preference*

The alternatives are ranked in descending order, with the highest relative closeness value indicating the best alternative and the optimal solution to the problem placed at the top of the list.

The results of the Relative Closeness C_i^* to the Ideal Solution calculation are presented in Table 11.

2. VIKOR

VIKOR is a compromise ranking method that was initially not classified as an MCDM method. Instead, it utilizes a methodology introduced in (Opricovic, 1998) to determine weight stability intervals. The notion of a compromise solution was introduced in (Yu, 1973). A compromise solution represents a feasible option that is closest to the ideal, and compromise denotes reaching an agreement through mutual concessions. Authors in (Opricovic, 1998) highlighted the suitability of the VIKOR method for implementation within MCDM. It is employed to select and rank alternatives in the presence of multiple conflicting criteria. The method utilizes a multicriteria ranking index, which measures the "closeness" to the ideal solution as proposed by (Opricovic, 1998) in 1998. Each alternative is evaluated based on each criterion, and the ranking is determined by comparing the measure of closeness to the ideal alternative.

In the following section, we explain step by step the sequence of this technique.

Step 1: *Constructing the decision matrix of the problem*

The decision matrix illustrates how different alternatives perform in relation to multiple criteria

$$[x_{ij}]_{mxn} = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}. \tag{11}$$

Step 2: *Determine the ideal and negative-ideal solutions*

The determination of ideal solution $A^*$and the negative ideal solution A^- is carried as follows:

$$\begin{aligned} A^* = &\{x_1^*, x_2^*, \ldots, x_j^*, x_n^*\} = \\ &\{(\max x_{ij} | j \in J') \, or \, (\min x_{ij} | j \in J'')\}, \\ &i = 1, 2, \ldots, m. \end{aligned} \tag{12}$$

$$\begin{aligned} A^- = &\{x_1^-, x_2^-, \ldots, x_j^-, x_n^-\} = \\ &\{(\min x_{ij}^* | j \in J') \, or \, (\max x_{ij}^* | j \in J'')\}, \\ &i = 1, 2, \ldots, m, \end{aligned} \tag{13}$$

where:

$$J = \{j = 1, \ldots, n | x_{ij}, \text{a larger response is desired}\}, \tag{14}$$

$$J' = \{j = 1, \ldots, n | x_{ij}, \text{a smaller response is desired}\}. \tag{15}$$

Step 3: *Calculate the utility measure and the regret measure*

The utility measure and the regret measure for each alternative are given as:

$$S_i = \sum_{j=1}^{n} w_j (x_j^* - x_{ij}) / (x_j^* - x_j^-), \tag{16}$$

$$R_i = \left[w_j (x_j^* - x_{ij}) / (x_j^* - x_j^-) \right], \tag{17}$$

where: S_i and R_i represent the utility measure and the regret measure, respectively, w_j denotes the weight of the j^{th} criterion and where x_j^* and x_j^- correspond to the ideal and negative-ideal solutions which are determined as follows:

Step 4: *Calculate the VIKOR index*

The VIKOR index can be expressed as follows:

$$Q_i = p \left[\frac{S_i - S^*}{S^- - S^*} \right] + (1 - p) \left[\frac{R_i - R^*}{R^- - R^*} \right], \tag{18}$$

where: Q_i represents the i^{th} alternative VIKOR value, $i = 1, \ldots, m$;

$$S^* = S_i, \quad S^- = S_i, \tag{19}$$

$$R^* = R_i, \quad S^- = R_i \tag{20}$$

and $p \in [0, 1]$ is the weight of the maximum group utility (and is usually set to 0.5).

Step 5: *Determine the preference ranking*

The alternative with the lowest VIKOR value is identified to be the best solution.

Step 6: *Propose a compromise solution* to the alternative A1 which is ranked as the best by the measure Q (minimum) if the following two conditions are satisfied:

Condition 1: Acceptable advantage: $QA2 - QA1 \geq DQ$, where $A2$ is the alternative with second position in the ranking list by Q; $DQ = 1/(n-1)$.

Condition 2: To ensure acceptable stability in decision making, it is necessary for alternative A1 to be ranked as the best option by S and/or R. This compromise solution demonstrates stability within the decision-making process and can be achieved through various approaches that include "voting by majority rule" (when $p > 0.5$ is required), "by consensus" ($p \approx 0.5$), or "with veto" ($p < 0.5$).

If one of the conditions is not satisfied, then a set of compromise solutions is proposed, which consists of:

- Alternatives A1 and A2 if only Condition 2 is not satisfied, or
- Alternatives A1, A2, ..., AN if Condition 1 is not satisfied; and AN is determined by the relation QAN − QA1<DQ for maximum N (the positions of these alternatives are "in closeness").

Phase 3

Table 11 presents the alternative rankings of TOPSIS, VIKOR & RPN.

Discussion

This section aims to assess the performance of MCDM techniques utilized in the analyzed problem. It is worth mentioning that the four criteria (Se, Oc, De, RI) considered in this study are assigned equal weights of 1.

Table 11 presents a comparative performance analysis of RPN, TOPSIS and VIKOR. The table clearly demonstrates the effectiveness of MCDM techniques in tackling complex problems, drawing inspiration from a specific case study. Additionally, the involvement of multiple decision-makers in TOPSIS and VIKOR further reinforces the robustness of these methods.

The proposed MCDMs are relatively straightforward to comprehend and implement. These techniques utilize a simple analysis framework that avoids complex mathematical computations, making them highly advantageous for decision-makers and robot users.

By applying MCDMs, it can be noticed that all acceptance conditions in MCDMs are met and confirmed, ensuring a satisfactory level of stability in the decision-

Table 11
TOPSIS & VIKOR results

TOPSIS					VIKOR					Risk priority number	
FM	D_i^*	D_i^-	C_i^*	**Rank**		S_i	R_i	Q_i	**Rank**	***RPN***	**Rank**
FM_1	0.4537	0.6565	0.5913	**1**		1.5946	0.8333	0.0494	**1**	937.50	**1**
FM_2	0.6393	0.3432	0.3493	**6**		2.4344	0.9524	0.6253	**6**	320.31	**4**
FM_3	0.6382	0.3445	0.3506	**5**		2.3803	0.9524	0.6112	**5**	312.50	**5**
FM_4	0.7883	0.3157	0.2860	**10**		2.9524	1.0000	0.9031	**10**	129.88	**7**
FM_5	0.7745	0.3407	0.3055	**8**		2.0875	1.0000	0.6778	**8**	86.13	**9**
FM_6	0.7743	0.3454	0.3085	**7**		2.0064	1.0000	0.6567	**7**	82.03	**10**
FM_7	0.5856	0.5723	0.4942	**3**		1.4794	0.9524	0.3766	**2**	322.66	**3**
FM_8	0.5825	0.5001	0.4619	**4**		1.7767	0.9524	0.4540	**3**	410.16	**2**
FM_9	0.5513	0.5425	0.4960	**2**		1.4048	1.0000	0.5000	**4**	271.88	**6**
FM_{10}	0.7757	0.3312	0.2992	**9**		2.2767	1.0000	0.7271	**9**	95.70	**8**
FM_{11}	0.8563	0.1001	0.1046	**12**		3.3243	1.0000	1.0000	**12**	10.94	**12**
FM_{12}	0.8383	0.1165	0.1220	**11**		3.1306	1.0000	0.9495	**11**	21.56	**11**
					$S^*.R^*$	1.4048	0.8333				
					$S^-.R^-$	3.3243	1.0000				

making process. Furthermore, the results demonstrate that the critical failure mode is Loose bolts/screws on (robot installation/cover/hand/robot arm) as it dominates a large portion of criteria. The FMECA team should attach great importance to this failure mode. A moderate degree of importance should be attributed to the mid-table failures modes which are Insecure connection of the power supply cable or hose damage in the pneumatic system drain.

Moreover, the least severe failures modes determined by VIKOR and TOPSIS methods for the Robot Mitsubishi RV-2AJ, are: cracks on the robot and controller cover, severe friction at the timing belt teeth and station shutdown. It should be noted that the proposed strategy enables engineers to monitor this system in order to benefit from the advantages of RI and prioritize sustainability and repairability in their daily operations.

Finally, the computational time required by MCDM methods is minimal, underscoring the efficiency of the proposed methodology. It is noteworthy that the calculation process of TOPSIS or VIKOR remains unaffected by the integration of additional parameters (criteria), ensuring the consistent application of this decision-making strategy.

Conclusion

In our research, we employed the FMECA method and acknowledged the difficulties associated with processing different failure modes solely based on RPN. As a result, our objective was to enhance the outcomes of the FMECA method by incorporating two MCDMs, namely TOPSIS and VIKOR, to support decision-makers in prioritizing the failure modes. Our study focused solely on TOPSIS and VIKOR, which yielded effective results in terms of ease and speed of execution. We believe that this approach can provide valuable assistance to decision-makers in their future decision-making processes.

We have also integrated the RI parameter as a criterion in our MCDM-based FMECA analysis, which incorporates environmental consciousness. We genuinely believe that this parameter has the potential to make a difference in sustainable decision-making in engineering design. In order to make it easily recognizable and distinguishable from traditional FMECA, we propose to name this approach "Green FMECA". This approach provides a comprehensive evaluation of the potential risks associated with a system or process and its impact on the environment, thus enabling designers to make informed decisions to mitigate these risks. The name "Green FMECA" conveys the essence of our approach, which is to prioritize environmental considerations in the decision-making process. It is simple, memorable, and easy to communicate, making it an ideal term for this approach. We believe that the "Green FMECA" approach has the potential to significantly enhance the sustainability and resilience of engineering systems and processes, and we look forward to its adoption and implementation in various contexts and industries.

As a future direction, we would like to incorporate fuzzy logic into our approach to enable more accurate and informed decisions, capable of handling uncertainty and imprecision in data.

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Appendix

Table 12
List of used initials

Abbreviation	**Full Term**
AHP	Analytical Hierarchy Process
ANP	Analytic Network Process
BWM	Best Worst Method
COPRAS	COmplex PRoportional ASsessment
DEMATEL	Decision Making Trial and Evaluation Laboratory
DSM	Design Structure Matrix
EDAS	Evaluation Based on Distance from Average Solution
ELECTRE	ELimination Et Choix Traduisant la REalité
ERVD	Election Based on Relative Value Distance
GRA	Grey Relational Analysis
IT2FSs	Interval Type-2 Fuzzy Sets
MAIRCAS	Multi-Attributive Ideal Real Comparative Analysis
MAIRCOS	Measurement of Alternatives and Ranking according to COmpromise Solution
MCDM	Multi-Criteria Decision-Making Methods
PROMETHEE	Preference ranking organization method for enrichment evaluation
q-ROFSs	q-rung orthopair fuzzy sets
RCM	Reliability Centered Maintenance
REV	Risk Expected Value
TODIM	TOmada de Decisão Interativa e Multicritério
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
VIKOR	VIseKriterijumska Optimizacija I Kompromisno Resenje
WASPAS	Fuzzy Weighted Aggregates Sum Product Assessment