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A nonparametric approach for failure mode prioritization in RCM: a case study in a petrochemical laboratory

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Abstract
The petrochemical company, a major producer of PTA in Indonesia, has an important laboratory to ensure product quality, with capillary electrophoresis as one of the vital instruments for determining quality. The maintenance strategy currently implemented, namely preventive and corrective maintenance, is not optimal in preventing sudden downtime. The Reliability Centered Maintenance (RCM) method is proposed as a more systematic approach. In the RCM process, Failure Mode and Effect Analysis (FMEA) is used to identify failure risks; however, the conventional FMEA method has limitations in determining the Risk Priority Number (RPN), which can result in identical values. This study uses the Reliability Centered Maintenance (RCM) method, which includes qualitative and quantitative analyses. One of the qualitative analyses is determining FMEA, with the output being the RPN value. The qualitative analysis of the RCM method resulted in identifying critical instruments and critical instrument capability limits, creating a critical instrument system block diagram, and identifying FMEA, which produced 45 critical instrument failure modes (FM). The quantitative study proposed a nonparametric statistical approach, namely the Mann-Whitney and Kruskal-Wallis tests, to optimize failure priority ranking. The Mann-Whitney test results for FM with two identical RPN values $(U_{value}>37;p>0.05)$ showed insignificant results and through expert consideration was able to distinguish priorities among 16 FM with identical RPN, while the Kruskal-Wallis test results for FM with more than two identical RPN values $(H_{value}<5.99;p>0.05)$ showed insignificant results and through expert consideration was able to distinguish priorities in 13 FM with three or more identical RPN values.

Keywords:
Capillary Electrophoresis;
FMEA;
Laboratory;
Nonparametric;
RCM;

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INTRODUCTION

Maintenance aims to ensure the system operates effectively and reliably [1], which in turn can increase productivity and customer satisfaction [2][3]. An optimal maintenance strategy is necessary in order to extend the life of instrument components and reduce potential instrument downtime. The maintenance strategy using the Reliability Centred Maintenance (RCM) method has been proven by previous research as a solution to minimise downtime and reduce costs through structured implementation that is easy to apply in various industries [4, 5, 6]. The RCM process is a combination of preventive maintenance, corrective maintenance, predictive maintenance, and proactive maintenance [4, 7, 8].

A petrochemical company in Merak, Banten, produces Purified Terephthalic Acid (PTA) as a raw material for polyethylene terephthalate (PET) plastic and polyester fiber. To ensure product quality, the laboratory requires an optimal instrument maintenance strategy. Currently, preventive and corrective maintenance are ineffective, as there were 521 unexpected downtimes between 2016 and 2024. This study uses systematic Reliability Centered Maintenance (RCM) to reduce unexpected downtime [8][9] and support the laboratory in the ISO17025 certification process [10][11]. The RCM method's maintenance strategy consists of two approaches: qualitative and quantitative [12][13]. The qualitative approach uses Failure Mode and Effect Analysis (FMEA) [14]. In contrast, the quantitative approach uses Risk Priority Number (RPN) calculations based on the criteria of Severity (S), Occurrence (O), and Detection (D) [15][16]. However, conventional FMEA has weaknesses; one is that it finds the same RPN value for different failure modes, making it difficult to determine priorities [17].

Conventional FMEA is still used in the RCM process, but requires optimization to facilitate priority determination. Previous studies have shown the application of FMEA in RCM in petrochemical plants [18][19], health laboratories [20][21], educational laboratories [11], and forensic laboratories [22], although research on RCM strategies in laboratories is still limited. Several specific studies include the maintenance of electron microscopes [23] and the maintenance of Continuous Emission Monitoring System (CEMS) instruments in environmental laboratories, which are useful for monitoring and measuring the concentration of exhaust gas emissions from industry [24]. Research on this more specific instrumentation serves as a guide for research in the process of determining maintenance strategies with RCM. Optimization of FMEA within the RCM method in laboratory research has never been conducted, one reason being the existence of identical RPN values. This research utilizes a nonparametric statistical approach, including the Mann-Whitney and Kruskall-Wallis tests, which aim to overcome the duplication of RPN values for each different failure mode, but do not determine the importance of the failure mode [25]. The advantage of nonparametric statistical testing is that it is distribution-free and can be used for ranking [26]. Based on the literature search, no research has been found that combines FMEA and nonparametric testing in RCM in laboratories. However, this method has been applied to asphalt mixtures [27] and the perception of cycling risks [28]. Based on previous research, this study aims to optimize FMEA with a nonparametric approach in petrochemical laboratory RCM, in order to produce a new model to overcome the duplication of RPN values and strengthen maintenance decision priorities.

METHOD

The stages of research to optimize the FMEA model with nonparametric statistics in the Reliability Centered Maintenance process are as follows: Figure 1 [9][21].

1. Determine critical instruments from laboratory data with Pareto diagrams.
2. Conduct a data search for specifications and operating systems of critical instruments.
3. Identifying experts and conducting group discussion forums.
4. Define specifications and operating systems of critical instruments.
5. Describe the operating system and Functional Block Diagram (FBD).
6. Identify the priority of failure modes in critical instrument components based on the ranking of FMEA RPN values.

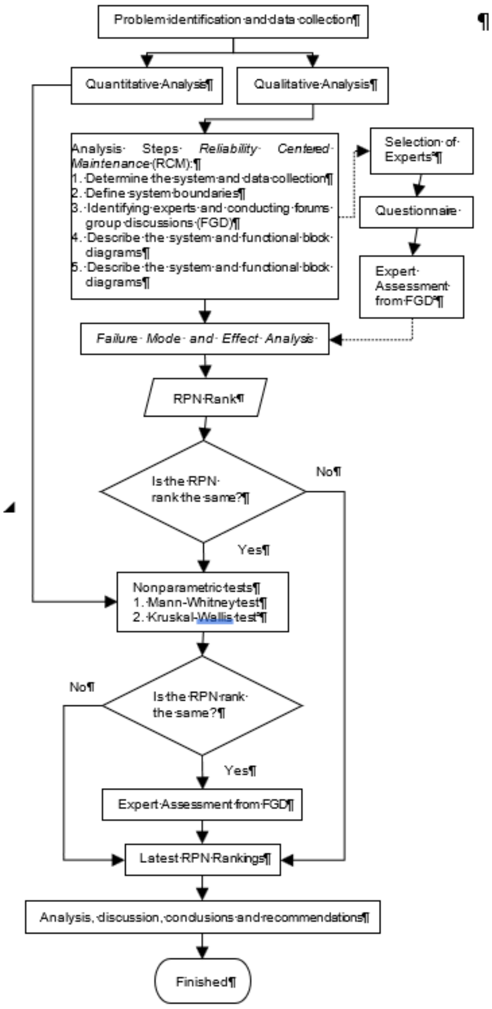


Figure 1. Research flow chart

7. Perform a nonparametric statistical test on the same RPN value to rank the failure modes.
8. Re-ranking the RPN values from the results of the nonparametric statistical test and evaluation by the laboratory maintenance team.

The experts selected in Figure 1 were selected based on education, experience, and position in the laboratory responsible for instrument maintenance. Four experts were selected from the laboratory, including two laboratory technicians, one instrument specialist, and one chemist. The questionnaire was created based on the results of risk identification through discussions with experts and data on instrument damage. We then verified the experts' opinions based on their experience and certification by the instrument distributor and compared them with the instrument manual. The questionnaire was completed by experts who gave scores during the discussion. An example of the questionnaire can be seen in Appendix 1.

Reliability Centered Maintenance (RCM)

RCM maintenance strategy is a systematic maintenance method that identifies operating system failures to maintain the reliability of the physical assets owned by the company [29]. The RCM approach is carried out reactively and proactively to prevent downtime that affects operations. The RCM process includes collecting research data, selecting critical instruments, identifying operating system failures with FMEA, applying RCM decision diagrams in determining maintenance types, and creating maintenance strategies [24].

Nonparametric Statistical Test

Nonparametric statistical tests are often referred to as distribution-free methods [26]. Nonparametric statistical tests are beneficial in making decisions when there is not enough information obtained, and the distribution of the sample data is not normal. The data is in ordinal and nominal form. A nonparametric statistical test method approach can be carried out based on these conditions. However, in the end, parametric statistical tests will be better than nonparametric statistical tests because the sample or population is known [30].

Mann-Whitney Test

The Mann-Whitney test is one of the nonparametric statistical tests used to determine whether two data sets come from independent samples and whether the data distribution is unknown. It is an alternative test to the t-test [31]. The Mann-Whitney test not only compares mean values but also finds out whether there is a significant difference in the distribution of values of the two groups being compared [32].

Kruskal-Wallis Test

The Kruskal-Wallis test is also one of the nonparametric tests used to determine three or more data sets that come from independent samples, and the data distribution is unknown [28]. Kruskal-Wallis test, an alternative test to the Analysis of Variance (ANOVA) test, was used to determine significant differences in medians in three or more groups being compared [27].

RESULTS AND DISCUSSION

Reliability Centered Maintenance (RCM) Analysis

Determine The System and Data Collection

The first step in implementing RCM is identifying critical instruments that often experience downtime. The determination of critical instruments is based on data on the damage history of all instruments owned by the laboratory in 2023, which often experience downtime. Instrument downtime data has been obtained for as many as 16 instruments from January 2023 to December 2023. Determination of critical instruments using a Pareto diagram [33]. Based on the Pareto diagram analysis, which can be seen in Figure 2, the capillary electrophoresis instrument experienced the most downtime in 2023, with 33 downtime events.

The results of information search efforts found that the maintenance system applied by the laboratory is preventive and corrective maintenance.

1. Preventive maintenance
   Implementation of preventive maintenance strategies on Capillary Electrophoresis instruments every 4 weeks. Figure 3 is an example of preventive maintenance activities in the laboratory, including cleaning the Capillary Electrophoresis instrument from dust with a vacuum cleaner.
2. Corrective maintenance
   Implementing corrective maintenance strategies in the laboratory is required when instrument components are damaged, and component replacement is required. One example of corrective maintenance activities in Figure 4 applied to Capillary Electrophoresis instruments is the replacement of Capillary Electrophoresis capillary columns.

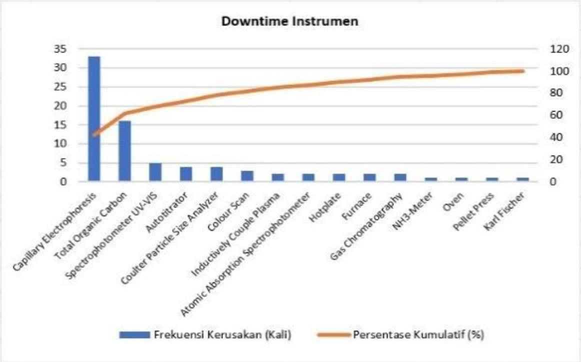


Figure 2. Pareto diagram of laboratory instruments

The research continued by describing the system and creating a functional block diagram (FBD).

System Description, System Limitations, and Functional Block Diagram

The next step is to describe the operating system based on the capillary electrophoresis instrument manual book and the Standard Operating Procedure (SOP) from the laboratory. A system description is carried out to determine the limitations of the maintenance system and to understand the working system of the Capillary Electrophoresis instrument. The Capillary Electrophoresis instrument checks the quality of Purified Terephtalic Acid (PTA) products on BA, 4-CBA, p-Tol, and HMBA parameters.

The four parameters are the most significant impurity levels in purified terephthalic acid products and are product quality parameters desired by both internal and external customers. Based on the Capillary Electrophoresis instrument design, the specifications below can be seen in Table 1.

Figure 3. Capillary electrophoresis cleaning process

Figure 4. Capillary column replacement

System descriptions sourced from instrument manuals and SOPs are beneficial in mitigating issues when components in CE instruments are not functioning correctly and in understanding the components of the instrument.

In the RCM process to facilitate understanding of the CE instrument operating system, a Functional Block Diagram (FBD) is made, which can be seen in Figure 5, to make it easier to understand the function of each component and facilitate mitigation if it experiences downtime.

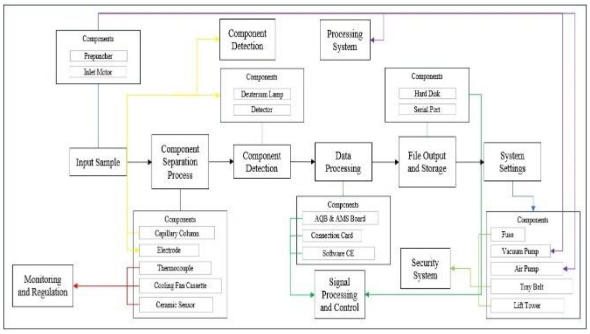


Figure 5. FBD capillary electrophoresis

Table 1. Physical specifications of capillary electrophoresis

Type	Specification	Comments
Weight	35 kg (77.2 lbs)	
Dimensions (width x depth x height)	350 x 510 x 590 mm (13.8 x 20.1 x 23.2 inches)	
Line voltage	100 - 240 VAC ± 10%	Wide-ranging capability
Line frequency	50 or 60 Hz ± 5%	
Power consumption	350 VA / 300 W / 1024 BTU/h	Maximum
Ambient operating temperature	5 - 40 °C (41 - 104 °F)	
Ambient non-operating temperature	-40 to 70 °C (-40 to 158 °F)	
Humidity	below 80% at 31 °C (87.8 °F)	Non-condensing
Operating altitude	Up to 2000 m (6500 ft)	
External cooling	max. 0.5 bar (7.2 psi), max. 50 °C (122 °F)	Water bath
External pressure	2 - 12 bar (29 - 174 psi)	Oil-free air or nitrogen
Safety standards: IEC, CSA, UL	Installation category II, Pollution degree 2	For indoor use only
Housing	All material is recyclable	

Some components in the CE instrument in Figure 5 are components in the CE system that function parallel, grouped into five parallel functions: monitoring and regulation, sample component detection, signal processing and control, processing system, and security system.

Determining System Functions and Functional Failures

Documentation of the causes of downtime is done using the RCM II information worksheet. Downtime that has occurred is carried out through an in-depth identification of CE instrument components that are no longer functioning. Discussions are held with the maintenance team to prevent similar downtime from occurring, which can interfere with laboratory productivity. As an example of the results of the RCM II information worksheet, capillary column, several failure modes in the capillary column component of the CE instrument are as follows:

1. Broken capillary column
   No compound separation occurs, blank electropherogram.
2. The outer layer of the capillary attached to the window cassette has not been removed
   Detector fails to read due to an obstructed Light.
3. Capillary column salting
   Precipitation clogs the capillary, and the signal does not appear.
4. Fused silica damage
   Compound separation fails due to damage from repeated flushing.
5. Buffer not degassed
   Air bubbles cause noise and flow disturbance.
6. Leak current due to air bubbles
   Overpressure damages capillaries and causes noise.
7. Buffer contaminated with water
   pH inaccuracy triggers noise in the separation process.
8. Uneven capillary column tip
   The signal baseline is skewed.
9. Leak current (yellow bar)
   Broken capillary causing leakage current.
10. Yellow bar due to bubbles
    Bubbles cause CE to be unable to analyze.
11. Laboratory room humidity exceeds 70%
    Causes a leak current, analysis fails.
12. Column length is not appropriate
    Compound separation is not optimal.

FMEA Analysis of CE Instrument

FMEA on CE instruments can identify the causes of component failures and their impact on the operating system. The RPN value in FMEA is the final result of the FMEA analysis to determine the failure modes that significantly impact downtime in CE instruments. The RPN value was obtained from an assessment by the laboratory maintenance team, consisting of four employees, who will fill out a questionnaire based on Severity, Occurrence, and Detection criteria on a scale of 1 to 10 [34]. The assessment criteria in Table 2 are adjusted to the actual laboratory conditions and refer to previous studies [34].

Table 2. Criteria for severity, occurrence, and detection levels

	Severity		Occurrence		Detection	
Rating	**Effect**	**Criteria**	**Effect**	**Criteria**	**Effect**	**Criteria**
1	No Impact	Minimal or no correction needed.	Almost never	No failures in the last 2 years.	Absolute Uncertainty	100% automatic inspection for defects. Defects or mechanical equipment maintenance are clearly visible.
2	Very Slight	Will be repaired by a technician soon.	Remote	1 or 2 failures in the last 2 years.	Very Remote	Almost 100% of all lathe machine parts are inspected automatically.
3	Slight	To be repaired immediately by an instrument technician.	Very slight	3 or 4 failures in the last 2 years.	Remote	Failures are often identified automatically and sometimes through manual inspection.
4	Minor	The components will gradually deteriorate if not repaired.	Slight	5 or 6 failures in the last 2 years.	Very Low	Machine failures are reported directly by the operator.
5	Moderate	The component is not performing its function, but failure maintenance does not require machine shutdown.	Low	7 or 8 failures in the last two years.	Low	The failure was identified by the maintenance team during a daily inspection.

Severity			Occurrence		Detection	
Rating	**Effect**	**Criteria**	**Effect**	**Criteria**	**Effect**	**Criteria**
6	Significant	Maintenance requires stopping the machine for one day or less.	Medium	9 or 10 failures in the last two years.	Moderate	The machine undergoes 100% manual inspection and observation.
7	Major	Maintenance requires stopping the machine for more than one day.	Moderately high	10 or 11 failures in the last 2 years.	Moderately High	Failures are identified by abnormal noises.
8	Extreme	The machine must be stopped and requires a longer repair time.	High	12 or 13 failures in the last 2 years	High	Failures are identified by conducting several tests and not just by direct inspection.
9	Serious	Severe machine failure disrupts system functionality.	Very high	14 or 15 failures in the last 2 years.	Very High	Failures are identified only through random or indirect testing.
10	Hazardous	May cause damage to machinery or humans.	Almost certain	More than 15 failures in the last 2 years.	Almost Certain	Hidden failures, impossible to identify by operators or maintenance teams.

The results of the questionnaire completed by the care team, which has more than 10 years of experience, were then grouped, and the RPN values were calculated. The next step was to calculate the percentage of the index for severity, occurrence, and detection using these [35].

$$S.I = \frac{\sum_{i=1}^{10} a_i n_i}{10N} \times 100\% \qquad O.I = \frac{\sum_{i=1}^{10} a_i n_i}{10N} \times 100\%$$

$$D.I = \frac{\sum_{i=1}^{10} a_i n_i}{10N} \times 100\%$$

The reference percentage values in Table 3.

The rating index in this study is based on previous research [35]. Where a_i is the number of levels in each criterion, the assessment criteria levels in this study are from 1 to 10. The description of the n_i is respondents' total score in completing each criterion's questionnaire. N is the number of experts who completed the questionnaire.

Table 3. Reference percentage value index [35]

Index Number	
Rating	**Index (%)**
1	0-10
2	11-20
3	21-30
4	31-40
5	41-50
6	51-60
7	61-70
8	71-80
9	81-90
10	91-100

The following is an example of calculations for the capillary column component with a broken capillary column failure mode using questionnaire data from four experts. The severity value is 6 for respondents 1 and 2, while the severity is 7 for respondents 3 and 4. The calculated severity index percentage is 65%.

The results of the calculation in the percentage index can be seen from the summary of the percentage index in severity, occurrence, and detection in Table 4.

Table 4. RPN calculation results

Spare part		Failure Mode	Index			RPN			RPN	Rank
			Severity (%)	**Occurrence (%)**	**Detection (%)**	**Severity**	**Occurrence**	**Detection**		
Capillary Column	1	Broken capillary column	65	40	82.5	7	4	9	252	5
	2	The outer layer of the capillary attached to the window cassette has not been removed.	62.5	20	52.5	7	2	6	84	12
	3	The capillary column is experiencing salting.	55	40	75	6	4	8	192	7
	4	The fused silica layer is damaged	52.5	20	92.5	6	2	10	120	9
	5	The buffer solution has not been degassed.	42.5	20	62.5	5	2	7	70	16
	6	Leakage current due to air bubbles	47.5	20	35	5	2	4	40	22
	7	Contamination of the buffer by water	25	20	47.5	3	2	5	30	24

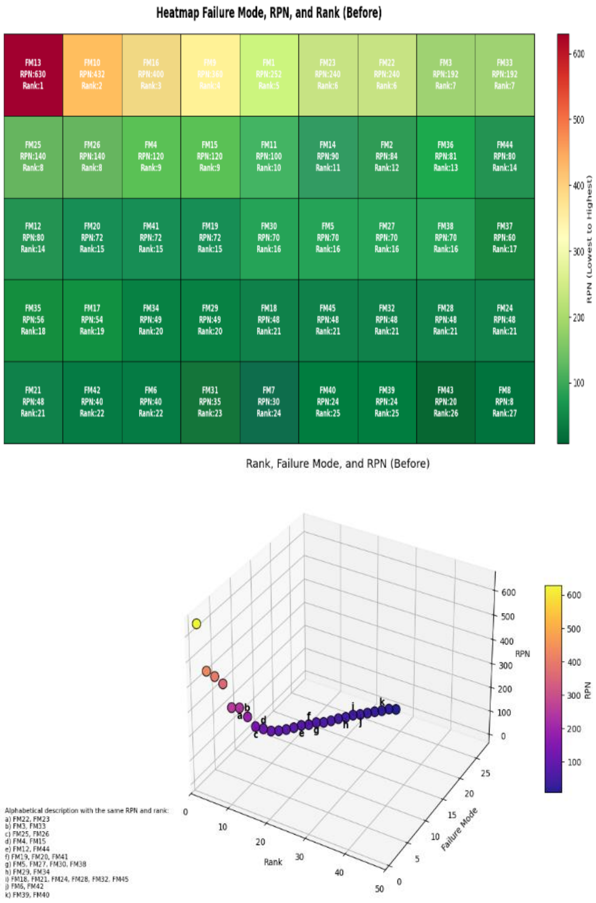
Spare part		Failure Mode	Index			RPN			RPN	Rank
			Severity (%)	Occurrence (%)	Detection (%)	Severity	Occurrence	Detection		
	8	The cut at the end of the capillary column is uneven.	20	20	20	2	2	2	8	27
	9	Leakage current indicated by a yellow bar	50	80	85	5	8	9	360	4
	10	A yellow bar appears on the CE software.	52.5	80	90	6	8	9	432	2
	11	The humidity in the laboratory exceeds 70%.	50	50	40	5	5	4	100	10
	12	Column length does not match	50	32.5	37.5	5	4	4	80	14
Deuterium Lamp	13	Low deuterium lamp intensity.	62.5	100	87.5	7	10	9	630	1
	14	The ignition part of the light is not working.	27.5	60	50	3	6	5	90	11
	15	The baseline signal on the electropherogram of low concentration samples is not good.	30	57.5	50	4	6	5	120	9
	16	Baseline signal response of deuterium lamp with low intensity on high concentration components.	50	80	92.5	5	8	10	400	3
	17	The intensity of the deuterium lamp decreases by more than 50% or more than 2000 hours after use.	82.5	10	57.5	9	1	6	54	19
Software Capillary Electrophoresis	18	The CE application cannot be opened.	20	60	40	2	6	4	48	21
	19	The computer's 4GB RAM capacity is 100% used.	22.5	60	40	3	6	4	72	15
	20	The CE application can be installed but cannot be operated on the Windows 11 operating system.	60	20	57.5	6	2	6	72	15
Electrode	21	Bent electrode.	55	10	77.5	6	1	8	48	21
	22	The presence of leak current.	52.5	50	72.5	6	5	8	240	6
	23	The electrode is salted.	55	50	80	6	5	8	240	6
	24	The rubber electrode is damaged.	55	10	80	6	1	8	48	21
Air Pump	25	The water pump rubber is torn.	65	20	100	7	2	10	140	8
	26	The Teflon air pump is torn.	65	20	100	7	2	10	140	8
	27	The pump motor smells burnt.	92.5	10	70	10	1	7	70	16
Cooling Fan Cassette	28	Cassette temperature overheated.	55	10	72.5	6	1	8	48	21
	29	The bearing on the cooling fan is worn out.	62.5	10	70	7	1	7	49	20
	30	The cooling fan is not spinning.	62.5	20	47.5	7	2	5	70	16
Lift Tower	31	Broken vial holder	62.5	10	42.5	7	1	5	35	23
	32	The motor in the lift tower is broken.	52.5	20	30	6	2	4	48	21
	33	Lift tower block.	60	30	72.5	6	4	8	192	7
Tray Belt	34	Weak tray belt	62.5	10	62.5	7	1	7	49	20
Hard Disk	35	Unable to access stored data	62.5	20	30	7	2	4	56	18
Automatic Quality Board (AQB) and Automatic Measurement System (AMS) Board	36	Unable to control the carousel when opening the CE software.	90	10	82.5	9	1	9	81	13
Ceramic dan Peltier Censor	37	The sensor is damaged.	60	10	100	6	1	10	60	17
Fuse	38	1.5 A fuse blown	62.5	10	100	7	1	10	70	16
Inlet Motor	39	The motor is damaged.	60	10	35	6	1	4	24	25
Connection Card	40	There is no connection between the CE software and the CE instrument.	60	10	32.5	6	1	4	24	25
Prepuncher	41	Prepuncher bent	55	20	60	6	2	6	72	15
	42	The prepuncher is salting	50	20	30	5	2	4	40	22
Serial Port	43	The RS sender wire is broken.	35	10	50	4	1	5	20	26
Thermocouple	44	Broken thermocouple cable	72.5	10	97.5	8	1	10	80	14
Power Supply	45	The power supply is damaged.	60	20	37.5	6	2	4	48	21

The results of the RPN calculation recapitulation in Table 4 show the RPN values from highest to lowest. The highest RPN indicates that the failure mode is the most dominant cause of downtime in the CE instrument. The largest RPN was found in the deuterium lamp component with a failure mode of low deuterium lamp intensity, with a value of 630, followed by the second largest RPN in the capillary column component with a failure mode of a yellow bar appearing in the CE software, with a value of 432, as can be seen in Figure 6. The highest RPN value is in accordance with the working principle of the CE instrument, whereby the deuterium lamp is the central spare part of the CE instrument for detecting sample components and is considered the heart of the instrument. In addition, deuterium lamps are costly and their production is limited. The second-highest RPN value is for the capillary column, which is where the sample components are separated, making the capillary column an important spare part after the deuterium lamp. The appearance of a yellow bar on the capillary column indicates a leak current, which prevents the CE instrument from analyzing samples. This can be caused by laboratory humidity below 80% and a maximum laboratory temperature of 31 °C, as shown in Table 1 The results of the first and second highest RPNs are in line with the experts' opinions during the FMEA discussion. The highest RPN results can assist the laboratory team in implementing continuous improvement related to the deuterium lamp, including modifying the new type of deuterium lamp socket for use in previous CE instrument models, as the previous deuterium lamp was produced in limited quantities. Furthermore, in the case of the yellow bar on the capillary column, a dehumidifier was added to reduce the humidity in the laboratory room. The following is a heatmap and scatter plot visualization to facilitate the determination of similar and different RPNs, which can be seen in Figure 6.

Based on Figure 6, it can be seen that the highest to lowest RPN from the heatmap visualization and scatter plot diagram still have the same RPN value and ranking, with the lowest scatter plot ranking around 20 to 30. The lowest RPN, with a value of 8 in the capillary column spare part, is cutting uneven capillary ends. This is the lowest because it does not interfere with separating components in the sample or detecting components in the sample. It only affects the visualization of the baseline signal line, which is not straight. Based on the lowest RPN, the laboratory team improved the procedure before replacing the new capillary column by cutting the capillary tip before using it on the CE instrument. The RPN recapitulation results also found the same RPN value, as seen in Figure 6. This is a weakness of using FMEA, so it is necessary to recalculate the RPN using nonparametric statistical tests to avoid the same RPN results in failure modes. The results of the RPN ranking in Table 4 and Figure 6 show 11 identical rankings with different failure modes. The RPN recalculation will be performed using nonparametric statistical tests to compare the groups of RPN component values.

Mann-Whitney Test

The Mann-Whitney test will be performed on the failure mode (FM) data in Table 5, which has the same RPN value consisting of two RPN: FM22, FM23, FM3, FM33, FM25, FM26, FM4, FM15, FM12, FM44, FM29, FM34, FM6, FM42, FM39, and FM40. The results of the Mann-Whitney test using Python can be seen in Table 5.



FM13 RPN:630 Rank:1	FM10 RPN:432 Rank:2	FM16 RPN:400 Rank:3	FM9 RPN:360 Rank:4	FM1 RPN:252 Rank:5	FM23 RPN:240 Rank:6	FM22 RPN:240 Rank:6	FM3 RPN:192 Rank:7	FM33 RPN:192 Rank:7
FM25 RPN:140 Rank:8	FM26 RPN:140 Rank:8	FM4 RPN:120 Rank:9	FM15 RPN:120 Rank:9	FM11 RPN:100 Rank:10	FM14 RPN:90 Rank:11	FM2 RPN:84 Rank:12	FM36 RPN:81 Rank:13	FM44 RPN:80 Rank:14
FM12 RPN:80 Rank:14	FM20 RPN:72 Rank:15	FM41 RPN:72 Rank:15	FM19 RPN:72 Rank:15	FM30 RPN:70 Rank:16	FM5 RPN:70 Rank:16	FM27 RPN:70 Rank:16	FM38 RPN:70 Rank:16	FM37 RPN:60 Rank:17
FM35 RPN:56 Rank:18	FM17 RPN:54 Rank:19	FM34 RPN:49 Rank:20	FM29 RPN:49 Rank:20	FM18 RPN:48 Rank:21	FM45 RPN:48 Rank:21	FM32 RPN:48 Rank:21	FM28 RPN:48 Rank:21	FM24 RPN:48 Rank:21
FM21 RPN:48 Rank:21	FM42 RPN:40 Rank:22	FM6 RPN:40 Rank:22	FM31 RPN:35 Rank:23	FM7 RPN:30 Rank:24	FM40 RPN:24 Rank:25	FM39 RPN:24 Rank:25	FM43 RPN:20 Rank:26	FM8 RPN:8 Rank:27

Alphabetical description with the same RPN and rank:
a) FM22, FM23
b) FM3, FM33
c) FM25, FM26
d) FM4, FM15
e) FM12, FM44
f) FM19, FM20, FM41
g) FM5, FM27, FM30, FM38
h) FM29, FM34
i) FM18, FM21, FM24, FM28, FM32, FM45
j) FM6, FM42
k) FM39, FM40

Figure 6. RPN visualisation (Before), heatmap (left) and scatter plot (right)

Table 5. RPN ranking results based on the Mann-Whitney test

Failure Mode	Mann-Whitney Test Results				
	Calculated U Value	**Rank value**	**FM Data Rankings**	**Test Result Decision**	**Rank RPN**
FM 22	U1=84	R1=138	1-8-16,5-19,5-22,5	60 > 37	2
FM 23	U2=60	R2=162	8-16,5-19,5-22,5	Not significant	1
FM 3	U1=72	R1=150	6,5-9,5-14,5-23,5	72 > 37	2
FM 33	U2=72	R2=150	2,5-14,5-20-22	Not significant	1
FM 25	U1=71	R1=151	4,5-10,5-14-16-20,5	71 > 37	1
FM 26	U2=73	R2=149	4,5-10,5-14-20,5	Not significant	2
FM 4	U1=63	R1=159	4-12,5-20-21,5-23,5	63 > 37	1
FM 15	U2=81	R2=141	4-8-9,5-12,5-17-21,5	Not significant	2
FM 12	U1=96	R1=126	6,5-10,5-14,5	48 > 37	2
FM 44	U2=48	R2=174	2,5-18-20-21-23	Not significant	1
FM 29	U1=60	R1=162	4,5-13-21	60 > 37	1
FM 34	U2=84	R2=138	4,5-13-21	Not significant	2
FM 6	U1=72	R1=150	5-12-16-20,5-24	72 > 37	1
FM 42	U2=72	R2=150	5-12-20,5	Not significant	2
FM 39	U1=70	R1=152	4,5-11-15-20,5	70 > 37	1
FM 40	U2=74	R2=148	4,5-11-15-20,5	Not significant	2

The overall failure mode test results in Table 5 reject H_0, which is insignificant, and a post hoc test cannot be performed. Ranking can also be determined by comparing the U values, although this is very weak in determining the better failure mode between the two groups. If the U value is low and the R value is high, then the distribution of the highest ranks is greater than the compared data group, and vice versa. If the U values are the same, then the distribution of ranks must be examined. Therefore, the better ranking between two FM is determined by the greater number of higher-ranking distributions. The same U value occurs when FM 3 and 33 are compared, followed by FM 6 and 42. Discussions with the four experts also reinforce the results of the FM ranking, and the results of the ranking are followed by nonparametric tests, along with the constraints in determining the failure mode ranking that have been explained previously [14].

Kruskal-Wallis Test

The Kruskal-Wallis test will be performed on failure mode (FM) data with the same RPN value of more than two RPN, including FM19, FM20, FM41, FM5, FM27, FM30, FM38, FM18, FM21, FM24, FM28, FM32, and FM45. The results of the Kruskal-Wallis test using Python can be seen in Table 6.

The overall failure mode test results in Table 6 reject H_0, which is insignificant, and a post hoc test cannot be performed. Ranking can also be determined by comparing the R values, although this is very weak in determining the better failure mode among more than two groups. If continued with a post hoc test using the Mann-Whitney test, a high R value means a low U value, giving it the first rank. A low U value indicates that the highest-ranking distribution is more frequent compared to the compared data group, and vice versa. Discussions with the four experts also support the results of the FM ranking determination and follow the results using nonparametric tests, along with the constraints in determining the failure mode ranking as previously explained.

Results of the Combination of Nonparametric Statistics and FMEA RPN

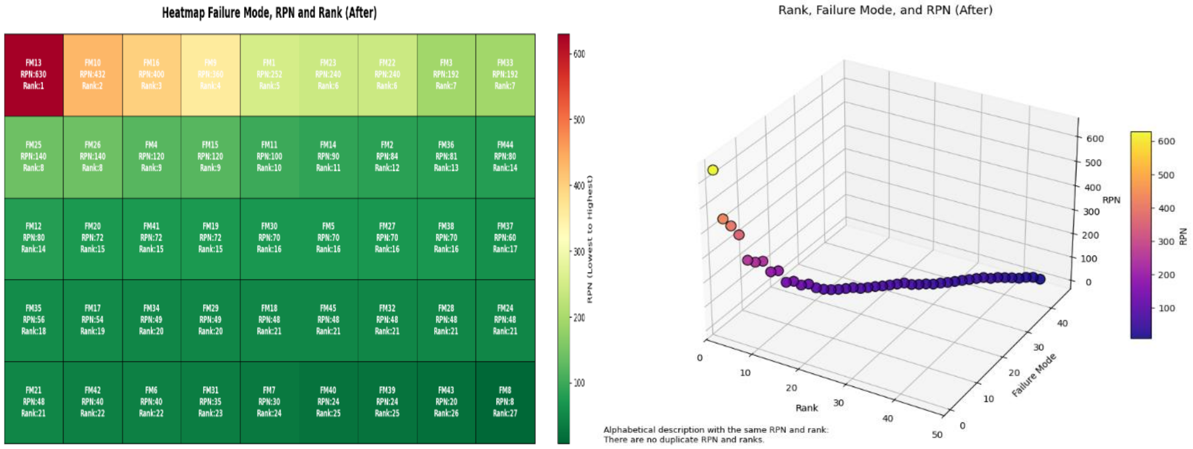
The results of the RPN value testing using nonparametric statistical tests produced a decision on the difference in rankings. The latest RPN rankings can be seen in Table 7. The FMEA study produced a ranking decision for each failure mode, but in conventional FMEA, the same RPN value was obtained for other failure modes, which is one of the weaknesses of FMEA [36]. Another weakness is the absence of expert weighting on each severity, occurrence, and detection rating scale [37]. This makes it difficult to make decisions when determining rankings. To overcome this problem, this study was conducted using a nonparametric statistical approach, including the Mann-Whitney and Kruskal-Wallis tests, which were used to determine the RPN ranking. The Mann-Whitney test compared two failure modes with the same RPN value. The test results showed that most pairs of failure modes did not show significant differences at a 95% confidence level. This means the same RPN values reflect similar risks in perception and available data. Some pairs with the same RPN values show that the rankings distribution indicates differences in the distribution of assessment data. With this approach, re-ranking becomes more objective. The Kruskal-Wallis test compared three or more failure modes with identical RPN values. Similar to the Mann-Whitney test results, no significant differences were found between groups at the 95% confidence level. A 95% confidence level is based on the consideration that an estimated value cannot be 100% reliable. Below is a visualization of the heatmap and scatter plot results of the combination of nonparametric statistics with FMEA, which can be seen in Figure 7. In the *heatmap* and *scatter plot* visualizations, the difference is very clear compared to Figure 6, in that there are no longer identical rankings for the same RPN values. This enables the laboratory team to determine the priorities for instrument improvements in the laboratory.

Table 6. RPN ranking results based on the Kruskal-Wallis test

Failure Mode	**Kruskall-Wallis Test Results**			
	Rank value	**Calculated H Value**	**Test Result Decision**	**Rank RPN**
FM 19	R1=200	H=0,590	0,590 < 5,99	3
FM 20	R2=238,5		Not significant	1
FM 41	R3=227,5			2
FM 5	R1=258	H=1,636	1,64 < 7,81	4
FM 27	R2=327		Not significant	1
FM 30	R3=268,5			3
FM 38	R4=322,5			2
FM 18	R1=428	H=1,714	1,74 < 11,07	5
FM 21	R2=474		Not significant	2
FM 24	R3=480			1
FM 28	R4=451,5			3
FM 32	R5=363			6
FM 45	R6=431,5			4

Table 7. Latest RPN calculation results

Failure Mode		**Index**			**RPN**			**RPN**	**New Rank**
		Severity (%)	**Occurrence (%)**	**Detection (%)**	**Severity**	**Occurrence**	**Detection**		
3	The capillary column is experiencing salting.	55	40	75	6	4	8	192	9
4	The fused silica layer is damaged	52.5	20	92.5	6	2	10	120	12
5	The buffer solution has not been degassed.	42.5	20	62.5	5	2	7	70	26
6	Leakage current due to air bubbles	47.5	20	35	5	2	4	40	38
12	Column length does not match	50	32.5	37.5	5	4	4	80	19
15	The baseline signal on the electropherogram of low concentration samples is not good.	30	57.5	50	4	6	5	120	13
18	The CE application cannot be opened.	20	60	40	2	6	4	48	36
19	The computer's 4GB RAM capacity is 100% used.	22.5	60	40	3	6	4	72	22
20	The CE application can be installed but cannot be operated on the Windows 11 operating system.	60	20	57.5	6	2	6	72	20
21	Bent electrode.	55	10	77.5	6	1	8	48	33
22	The presence of leak current.	52.5	50	72.5	6	5	8	240	7
23	The electrode is salted.	55	50	80	6	5	8	240	6
24	The rubber electrode is damaged.	55	10	80	6	1	8	48	32
25	The water pump rubber is torn.	65	20	100	7	2	10	140	10
26	The Teflon air pump is torn.	65	20	100	7	2	10	140	11
27	The pump motor smells burnt.	92.5	10	70	10	1	7	70	23
28	Cassette temperature overheated.	55	10	72.5	6	1	8	48	34
29	The bearing on the cooling fan is worn out.	62.5	10	70	7	1	7	49	30
30	The cooling fan is not spinning.	62.5	20	47.5	7	2	5	70	25
32	The motor in the lift tower is broken.	52.5	20	30	6	2	4	48	37
33	Lift tower block.	60	30	72.5	6	4	8	192	8
34	Weak tray belt	62.5	10	62.5	7	1	7	49	31
38	1.5 A fuse blown	62.5	10	100	7	1	10	70	24
39	The motor is damaged.	60	10	35	6	1	4	24	42
40	There is no connection between the CE software and the CE instrument.	60	10	32.5	6	1	4	24	43
41	Prepuncher bent	55	20	60	6	2	6	72	21
42	The prepuncher is salting	50	20	30	5	2	4	40	39
44	Broken thermocouple cable	72.5	10	97.5	8	1	10	80	18
45	The power supply is damaged.	60	20	37.5	6	2	4	48	35



Heatmap Failure Mode, RPN and Rank (After)

FM13 RPN:630 Rank:1	FM10 RPN:432 Rank:2	FM16 RPN:400 Rank:3	FM9 RPN:360 Rank:4	FM1 RPN:252 Rank:5	FM23 RPN:240 Rank:6	FM22 RPN:240 Rank:6	FM3 RPN:192 Rank:7	FM33 RPN:192 Rank:7
FM25 RPN:140 Rank:8	FM26 RPN:140 Rank:8	FM4 RPN:120 Rank:9	FM15 RPN:120 Rank:9	FM11 RPN:100 Rank:10	FM14 RPN:90 Rank:11	FM2 RPN:84 Rank:12	FM36 RPN:81 Rank:13	FM44 RPN:80 Rank:14
FM12 RPN:80 Rank:14	FM20 RPN:72 Rank:15	FM41 RPN:72 Rank:15	FM19 RPN:72 Rank:15	FM30 RPN:70 Rank:16	FM5 RPN:70 Rank:16	FM27 RPN:70 Rank:16	FM38 RPN:70 Rank:16	FM37 RPN:60 Rank:17
FM35 RPN:56 Rank:18	FM17 RPN:54 Rank:19	FM34 RPN:49 Rank:20	FM29 RPN:49 Rank:20	FM18 RPN:48 Rank:21	FM45 RPN:48 Rank:21	FM32 RPN:48 Rank:21	FM28 RPN:48 Rank:21	FM24 RPN:48 Rank:21
FM21 RPN:48 Rank:21	FM42 RPN:40 Rank:22	FM6 RPN:40 Rank:22	FM31 RPN:35 Rank:23	FM7 RPN:30 Rank:24	FM40 RPN:24 Rank:25	FM39 RPN:24 Rank:25	FM43 RPN:20 Rank:26	FM8 RPN:8 Rank:27

Alphabetical description with the same RPN and rank:
There are no duplicate RPN and ranks.

Figure 7. RPN visualisation (After), heatmap (left) and scatter plot (right)

Additionally, using a 95% confidence level based on the data available to the researcher has limitations, such as insufficient attention to the data recording process for component failures in the Capillary Electrophoresis instrument. A confidence level above 95% requires high costs and a long time, while a confidence level below 95% indicates insufficient data. The relationship revealed in the previous study produced a graph illustrating the determination of the confidence interval, which can be seen in Figure 8.

Overall, the FMEA method with a nonparametric statistical approach improves accuracy in determining the ranking of failure modes. This allows the laboratory maintenance team to focus on components that significantly impact instrument reliability, such as deuterium lamps with the highest RPN value of 630 and capillary columns with an RPN value of 432. Nonparametric tests have proven effective in overcoming equal RPN values that can influence decisions in prioritizing instrument maintenance. The weakness of this study is that the final results of the nonparametric test still depend on expert opinion, so this study does not end with the determination of the nonparametric test.

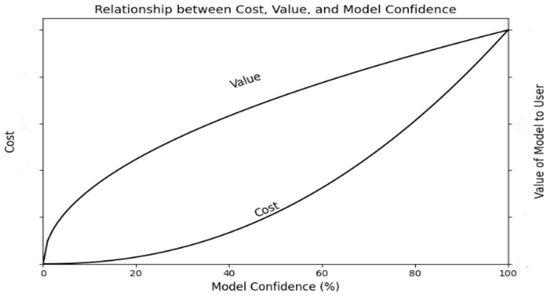


Figure 8. Model confidence interval [38]

The researchers continue their research because there are still stages in implementing RCM at the laboratory.

CONCLUSION

This study proves that the conventional Failure Mode and Effect Analysis (FMEA) method has limitations in providing accurate priority results, especially when several failure modes have the same Risk Priority Number (RPN) value. Using the Mann-Whitney and Kruskal-Wallis tests, a nonparametric statistical approach was employed to address this issue. The Mann-Whitney test separated failure modes with two identical RPN values, while the Kruskal-Wallis test effectively separated three or more identical RPN values. These two tests successfully provided a more objective and accurate re-ranking of failure modes.

The combination of the FMEA method and nonparametric statistics produces a more informative priority ranking of failure modes. These findings provide a stronger basis for laboratories in determining the priority of maintenance actions for critical instruments, resulting in a more focused maintenance strategy, minimized downtime, and a significant improvement in laboratory system reliability. The results of this combination are also readily applicable to the petrochemical and other industries.

Research combining FMEA with nonparametric statistics still has weaknesses. If the RPN value remains the same after discussions with experts, determining the FM priority requires time to reach a decision. Therefore, this research was continued by combining FMEA with *Fuzzy* to overcome the previous limitations.

REFERENCES

[1] A. S. Alkabaa *et al.*, “A fuzzy ANP-Based Criticality Analyses Approach of Reliability-Centered Maintenance for CNC Lathe Machine Components'', *J. Radiat Res Appl Sci*, vol. 17, no. 1, pp. 1–9, Mar. 2024, doi: 10.1016/j.jrras.2023.100738.

[2] A. Karevan et al., “A Reliability-Based and Sustainability-Informed Maintenance Optimization Considering Risk Attitudes for Telecommunications Equipment”, *Int’l J. Qua. Relia. Manag* vol. 38, no. 4, pp. 873–891, Mar. 2021, doi: 10.1108/IJQRM-04-2020-0114.

[3] S. Cahyati et al., “Optimization of Preventive Maintenance on Critical Machines at The Sabiz 1 Plant Using Reliability-Centered Maintenance method”, *Sinergi*, vol. 28, no. 2, pp. 355–368, 2024, doi: 10.22441/sinergi.2024.2.015.

[4] G. E. Omozuhiomwen et al., “Reliability–Centered Maintenance Using Reliability Parameters on Gas Compressors”, *Int’l J. Manuf. Mat. Mech. Eng.,* vol. 14, no. 1, pp. 1–31, 2025, doi: 10.4018/IJMMME.367256.

[5] R. F. da Silva et al., “Reliability and Risk Centered Maintenance: A Novel Method for Supporting Maintenance Management”, *Applied Sciences*, vol. 13, no. 19, pp. 1–23, Oct. 2023, doi: 10.3390/app131910605.

[6] T. Wang et al., “A Reliability-Centered Maintenance Framework for Distribution Grids Based on Fault-Tree Analysis”, in *Proc. Asia Paci. Conf. Progn. and Health Manag.,* Tokyo, Japan: PHM Society Asia-Pacific Conference, Sep. 2023, pp. 1–5. doi: 10.36001/phmap.2023. v4i1.3734.

[7] S. S. Patil et al., “Development of Optimized Maintenance Program for a Steam Boiler System Using Reliability-Centered Maintenance Approach”, *Sustainability*, vol. 14, no. 16, pp. 1–20, Aug. 2022, doi: 10.3390/su141610073.

[8] O. P. Bohrey and A. S. Chatpalliwar, “Application of Reliability Centred Maintenance in Improving Aircraft Availability with Preventive Maintenance Intervention”, *J. Adv. Res. App. Scie. Eng. Tech.*, vol. 42, no. 1, pp. 115–129, Dec. 2024, doi: 10.37934/araset.42.1.115129.

[9] O. D. Adenuga et al., “Development of Maintenance Management Strategy Based on Reliability Centered Maintenance for Marginal Oilfield Production Facilities”, *Engineering*, vol. 15, no. 03, pp. 143–162, 2023, doi: 10.4236/eng.2023.153012.

[10] J. L. Castro Valdivia et al., “Application of Reliability Centered Maintenance Tools to Standardize Processes Required by ISO/IEC 17025”, in *Proc. LACCEI Multi-conf. Eng. Edu. and Tech.* Florida, USA: Jul. 2022. doi: 10.18687/LACCEI2022.1.1.704.

[11] R. S. Arenhart et al., “Contribution Evaluation of The Maintenance Plans Based on Reliability Centered Maintenance for Measuring Instruments in Public Higher Education Institutions”, *Braz. J. Ope. and Pro. Manag.*, vol. 17, no. 2, pp. 1–16, Jun. 2020, doi: 10.14488/BJOPM.2020.020.

[12] D. Septiyana *et al.*, “ANFIS method to enhance FMEA water operation model of Indonesia drinking water distribution system”, *Sinergi*, vol. 29, no. 1, pp. 175–184, 2025, doi: 10.22441/sinergi.2025.1.016.

[13] M. Ulfah and P. F. Ferdinant, “Proposal for Maintenance of H-draw Press Machines in the Stamping Press Division Using the Reliability Centred Maintenance and Reliability Centred Spares Methods (Case Study: PT. TMMI)”, *J. Ind. Serv.*, vol. 7, no. 1, pp. 106–111, Nov. 2021, doi: 10.36055/jiss.v7i1.12777.

[14] L. O. Iheukwumere-Esotu and A. Yunusa-Kaltungo, “Knowledge management and experience transfer in major maintenance activities: A practitioner’s perspective”, *Sustainability*, vol. 14, no. 1, pp. 1–26, Jan. 2022, doi: 10.3390/su14010052.

[15] M. C. Jena et al., “Integration of Industry 4.0 with reliability centered maintenance to enhance sustainable manufacturing”, *Env. Prog Sust. Energ.* vol. 43, no. 2, pp. 1–9, Mar. 2024, doi: 10.1002/ep.14321.

[16] G. Kharmanda et al., “An Overview of Reliability Centered Maintenance Using Failure Mode and Effect Analysis”, *Incertitudes et fiabilité des systèmes multiphysiques*, vol. 7, no. 2, pp. 1–19, Dec. 2023, doi: 10.21494/iste.op.2023.1045.

[17] A. P. Subriadi and N. F. Najwa, “The Consistency Analysis of Failure Mode and Effect Analysis (FMEA) in Information Technology Risk Assessment”, *Heliyon*, vol. 6, no. 1, pp. 1–12, Jan. 2020, doi: 10.1016/j.heliyon.2020.e03161.

[18] W. H. Wang et al., “Application of the reliability-centered maintenance techniques for dynamic equipment in the petrochemical ammonia-related systems”, in *E3S Web of Conferences*, EDP Sciences, May 2023, pp. 1–6. doi: 10.1051/e3sconf/202338504014.

[19] S. M. S. Hosseini et al., “Functional Model of Integrated Maintenance in Petrochemical

Industries", *Int'l J. Eng. Trans. B: App.* vol. 37, no. 6, pp. 1106–1117, Jun. 2024, doi: 10.5829/ije.2024.37.06c.07.

[20] S. Lv et al., "Application of the FMEA Method in Improving the Quality Management of Emergency Complete Blood Count Testing", *Lab Medicine*, vol. 54, no. 6, pp. 574–581, Nov. 2023, doi: 10.1093/labmed/lmad002.

[21] A. Shamayleh, M. Awad, and A. O. Abdulla, "Criticality-based reliability-centered maintenance for healthcare", *J Qual Maint Eng*, vol. 26, no. 2, pp. 311–334, Mar. 2020, doi: 10.1108/JQME-10-2018-0084.

[22] M. Asif, A. A. Zaidi, and S. Ahmed, "Reliability Centered Maintenance (RCM) of a Commercial HVAC Air Handling and Condensing Unit", *Euro. J. Adv, Eng. and Tec.*, vol. 7, no. 7, pp. 1–6, 2020, doi: 10.5281/zenodo.10667152v.

[23] J. Dias, E. Nunes, and S. Sousa, 'Productivity Improvement of Transmission Electron Microscopes - a Case Study', in *Proc. Manufact.,* Athens, Greece: Elsevier B.V., 2020, pp. 1559–1566. doi: 10.1016/j.promfg.2020.10.217.

[24] Y. J. Yang *et al.*, "Applying Reliability Centered Maintenance (RCM) to Sampling Subsystem in Continuous Emission Monitoring System", *IEEE Access*, vol. 8, pp. 55054–55062, 2020, doi: 10.1109/ACCESS.2020.2980630.

[25] T. Parr, J. Hamrick, and J. D. Wilson, "Nonparametric feature impact and importance", *Inf Sci (NY)*, vol. 653, p. 119563, 2024, doi: 10.1016/j.ins.2023.119563.

[26] N. Deb and B. and Sen, "Multivariate Rank-Based Distribution-Free Nonparametric Testing Using Measure Transportation", *J. Am Stat Assoc*, vol. 118, no. 541, pp. 192–207, Jan. 2023, doi: 10.1080/01621459.2021. 1923508.

[27] G. S. Moussa, A. Abdel-Raheem, and T. Abdel-Wahed, "Effect of nanoclay particles on the performance of highdensity polyethylene-modified asphalt concrete mixture", *Polymers (Basel)*, vol. 13, no. 3, pp. 1–23, Feb. 2021, doi: 10.3390/polym13030434.

[28] M. Bixhaku, G. Hoxha, and R. Duraku, "Analysis of Perceptions of Cycling Safety on Roads with Mixed Traffic Depending on Age, Gender, and Riding Experience", *Civil Eng. J.* vol. 9, pp. 141–151, Oct. 2023, doi: 10.28991/cej-sp2023-09-011.

[29] N. Rodríguez-Padial et al., "Assisted-Driven Design of Customized Maintenance Plans for Industrial Plants", *App. Scie.*, vol. 12, no. 14, pp. 1–19, Jul. 2022, doi: 10.3390/app12147144.

[30] J. C. Malela-Majika, "Nonparametric precedence chart with repetitive sampling", *Stat*, vol. 12, no. 1, pp. 1–13, Jan. 2023, doi: 10.1002/sta4.512.

[31] J. D. Karch, "Psychologists Should Use Brunner-Munzel's Instead of Mann-Whitney's U Test as the Default Nonparametric Procedure", *Adv Methods Pract Psychol Sci*, vol. 4, no. 2, pp. 1–14, 2021, doi: 10.1177/2515245921999602.

[32] P. D. Glenn II et al., "Artificial Intelligence and Machine Learning with Moment Generating Functions to Enhance Biological Count Data Analysis", *Molecu. Scie. and App.,* vol. 4, pp. 42–45, Oct. 2024, doi: 10.37394/232023.2024.4.5.

[33] N. Sembiring and D. V. K. Deli, "The strategy improvement of the engine maintenance", in *IOP Conference Series: Materials Science and Engineering*, Institute of Physics Publishing, Jul. 2020, pp. 1–7. doi: 10.1088/1757-899X/852/1/012115.

[34] G. Gupta and R. P. Mishra, "Comparative analysis of traditional and fuzzy FMECA approach for criticality analysis of conventional lathe machine", *Int'l J. Sys. Ass. Eng. and Manag.*, vol. 11, pp. 379–386, Jul. 2020, doi: 10.1007/s13198-019-00938-y.

[35] F. Izzati, "Underwater Pipeline Risk Analysis Using Fishbone Diagram and Fuzzy Failure Mode and Effect Analysis (FMEA) Methods", *Thesis*, Surabaya, Jul. 2022.

[36] E. Bartolomé and P. Benítez, "Failure mode and effect analysis (FMEA) to improve collaborative project-based learning: Case study of a Study and Research Path in mechanical engineering", *Int'l J. Mech. Eng. Edu. ,* vol. 50, no. 2, pp. 291–325, Apr. 2022, doi: 10.1177/0306419021999046.

[37] M. Yazdi, "Enhancing System Safety and Reliability through Integrated FMEA and Game Theory: A Multi-Factor Approach", *Safety*, vol. 10, no. 1, pp. 1–35, Mar. 2024, doi: 10.3390/safety10010004

[38] R. G. Sargent, "Verification and Validation of Simulation Models: An Advanced Tutorial', in *Proceedings - Winter Simulation Conference*, Institute of Electrical and Electronics Engineers Inc., Dec. 2020, pp. 16–29. doi: 10.1109/WSC48552.2020.9384052.

Appendix 1. Example of an FMEA questionnaire from expert 1

Sparepart		Failure Mode	Severity										Occurrence										Detection									
			Minimal or no correction needed.	Will be repaired by a technician soon.	To be repaired immediately by an instrument technician.	The components will gradually deteriorate if not repaired.	The component is not performing its function, but failure maintenance does not require machine shutdown.	Maintenance requires stopping the machine for one day or less.	Maintenance requires stopping the machine for more than one day.	The machine must be stopped and requires a longer repair time.	Severe machine failure disrupts system functionality.	May cause damage to machinery or humans.	No failures in the last 2 years.	1 or 2 failures in the last 2 years.	3 or 4 failures in the last 2 years.	5 or 6 failures in the last 2 years.	7 or 8 failures in the last two years.	9 or 10 failures in the last two years.	10 or 11 failures in the last 2 years.	12 or 13 failures in the last 2 years.	14 or 15 failures in the last 2 years.	More than 15 failures in the last 2 years.	100% automatic inspection for defects. Defects or mechanical equipment maintenance are clearly visible.	Almost 100% of all the machine parts are inspected automatically.	Failures are often identified automatically and sometimes through manual inspection.	Machine failures are reported directly by the operator.	The failure was identified by the maintenance team during a daily inspection.	The machine undergoes 100% manual inspection and observation.	Failures are identified by abnormal noises.	Failures are identified by conducting several tests and not just by direct inspection.	Failures are identified only through random or indirect testing.	Hidden failures, impossible to identify by operators or maintenance teams.
			1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10	1	2	3	4	5	6	7	8	9	10
Capillary Column	1	Broken capillary column						x								x														x		
	2	The outer layer of the capillary attached to the window cassette has not been removed.						x						x											x							
	3	The capillary column is experiencing salting.					x									x												x				
	4	The fused silica layer is damaged					x							x																x		
	5	The buffer solution has not been degassed.				x								x											x							
	6	Leakage current due to air bubbles				x								x										x								
	7	Contamination of buffer by water		x										x											x							
	8	The cut at the end of the capillary column is uneven.		x										x										x								
	9	Leakage current indicated by a yellow bar					x													x										x		
	10	A yellow bar appears on the CE software.					x													x											x	
	11	The humidity in the laboratory exceeds 70%.					x										x									x						
	12	Column length does not match					x								x											x						
Deuterium Lamp	13	Low deuterium lamp intensity.						x														x								x		
	14	The ignition part of the light is not working.		x														x								x						
	15	The baseline signal on the electropherogram of low concentration samples is not good.		x														x								x						
	16	Baseline signal response of deuterium lamp with low intensity on high concentration components.					x													x											x	
	17	The intensity of the deuterium lamp decreases by more than 50% or more than 2000 hours after use.								x			x															x				
Software Capillary Electrophoresis	18	The CE application cannot be opened.		x														x								x						
	19	The computer's 4GB RAM capacity is 100% used.		x														x								x						
	20	The CE application can be installed but cannot be operated on the Windows 11 operating system.						x						x														x				
Electrode	21	Bent electrode.					x						x															x				
	22	The presence of leak current.					x										x								x							
	23	The electrode is salted.					x										x											x				
	24	The rubber electrode is damaged.					x						x																	x		
Air Pump	25	The water pump rubber is torn.						x						x																		x
	26	The Teflon air pump is torn.						x						x																		x
	27	The pump motor smells burnt.									x		x																x			
Cooling Fan Cassette	28	Cassette temperature overheated.					x						x																	x		
	29	The bearing on the cooling fan is worn out.						x					x																x			
	30	The cooling fan is not spinning.						x						x												x						
Lift Tower	31	Broken vial holder						x					x												x							
	32	The motor in the lift tower is broken.					x							x											x							
	33	Lift tower block.						x							x														x			
Tray Belt	34	Weak tray belt						x					x															x				
Hard Disk	35	Unable to access stored data						x						x											x							
Automatic Quality Board (AQB) dan Automatic Measurement System (AMS) Board	36	Unable to control the carousel when opening the CE software.									x		x																			x
Ceramic dan Peltier Sensor	37	The sensor is damaged.						x					x																			x
Fuse	38	1.5 A fuse blown						x					x																			x
Inlet Motor	39	The motor is damaged.						x					x												x							
Connection Card	40	There is no connection between the CE software and the CE instrument.						x					x												x							
Prepuncher	41	Prepuncher bent					x							x														x				
	42	The prepuncher is salting					x							x											x							
Serial Port	43	The RS sender wire is broken.			x								x												x							
Thermocouple	44	Broken thermocouple cable							x				x																			x
Power Supply	45	The power supply is damaged.						x						x											x							