Improving Industrial Production Quality Assurance: An Analysis of MCDM and FMEA Methodologies

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Abstract: - The modern business context is so cut-throat, therefore, organizations should place emphasis on process leadership in the quest to provide the best quality products to their clients. Quality management practices that incorporate FMEA are a significant measure that can help in finding and solving issues with high impacts. This study deals the technique called (FMEA) and that its character is forward-looking, which means that it could identify, prioritize and eliminate slots leading to different sort of failures, that result in optimal performance and customer satisfaction. Study makes use of FMEA as an important component of the quality management system by interconnecting it with other approaches like Six Sigma, TQM and ISO 9001, which could bring these paradigms to even higher level, if implemented properly. From this case studies and good practices from real organizations, we will discuss strategic benefits of applying FMEA into management practices of quality as well as affecting versatility for different scenarious. A FMEA method is an engineering methodology designed to detect and eliminate problems in systems, designs, processes and solution that may happen and thus prevent loss of resources due to mistakes made by users. The study researches the application of FMEA tool in the area of quality improvement. Indeed, with FMEA aiming to improve efficiency through the prioritization of these types of errors and the focus on the errors of highest risk priority. It is also provided with the high tech machinery required for industrial grade cables producing for automotive and electronic industries. Via FMEA methodology, the study reviewed error situations, which had a chance of happening after the product has been used by the customer. The study, additionally, used MCDM (Multi-Criteria Decision-Making) techniques to upgraded decision-making available at the FMEA analysis at the same time. What could be pointed out as its main feature is the key role of FMEA as a strategic tool. It could allow organization to reach world-class level in different areas by simply grasping its theoretical and practical fundamentals.

Key-Words: - **:** FMEA (Failure Modes and Effects Analysis), Quality Management, Risk Assessment, Process Optimization, Maintenance, Corrective Actions, Process Efficiency, MABAC, MULTIMOORA, fuzzy Grey Relational Analysis (GRA)

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1 Introduction

The continuous battle of the modern business is to uphold the same quality and standards and improve them if possible for their organizations to remain competitive against their peers by consumers who strive for top-notch service. In this regard, quality management is a crucial component that entails the use of the multiple quality control tools and techniques for the progress over time. A FMEA is equally an indispensable tool along with Failure Modes and Effects Analysis (FMEA). For the last 5 years, the quality has not only been one of the most critical types of the competitive advantage but also has proved to be an essential one. In the modern-day market, being a step ahead in sustain the high standards of quality is crucial for long time well being. As a result, businesses of various kinds introduce different measures to make sure and increment quality of a product and/or service. It translates into continuous making efforts to identify and discard any factors that may have an adverse effect on the quality of the products or services and, on the other hand, gives the customers satisfaction level a corresponding turn. Abundant kinds of methods to be applied for quality and process improvement, the failure mode and effects analysis method has the considerable position. Through the use of FMEA, organizational reliability and quality are systemically enhanced by means of a systematic elimination of errors, a minimum fail-safe measurement, and a reduction of the vulnerability of making mistakes.

This section will specifically address FMEA's important role in quality management as a significant element of process improvement (where a few strategies will be mentioned). With time organizations face more challenging and demanding markets. The active detection and prevention of risks stands out as one of the most significant in this case. FMEA is a systematic and preemptive tool that helps threat assessment. If evaluates potential flaws in processes, systems, and products. Failure modes of these are identified, prioritized and subsequently rectified. The intention of this application is to look into the main concepts of FMEA and the approach to involving this method into the quality management systems. Through awareness of rapid FMEA feature, companies can use it to attain perfection, imagine their processes, avoid mistakes, and result in better results. The forthcoming discussions are going to be accompanied by case studies and examples of good practice, which are singling out FMEA implementation as a useful improvement contributor for many processes and products quality.
Moreover, the talk identified the competitive advantages of linking FMEA with the always used quality management techniques such as Six Sigma and TQM. FMEA and ISO 9001 synergies underlined in this regard which shows that these frameworks effectively work together committing to a continuous improvement and adherence to industry standards.
Simply speaking, the above introductory part gives a general overview of how FMEA is utilized in quality management. Over time, when organizations come across a challenge or are competing with their peers, FMEA gets to be more and more important as it not only stops or reduces risks in the production process but also continues to improve the organization to last in the sector.

2 Literature Survey

The whole FMEA literature is about importance of the topic and strategic application in order to raise current processes. This section starts with reviewing the existent literature as a basis on which to build a deeper understanding of FMEA in the light of improving the quality of business processes.

Many academic papers give extraordinary emphasis to FMEA's proactive character since it, among others, identifies and mitigates risks and problems in various fields of practice [1], [2], [3], [4], [5]. Crunching down on the problem, some researchers again highlight that, through FMEA, one would be able to not only identify faults, but also reliability and risk minimization, before the customers are affected. The literature agrees with the idea that FMEA's thorough approach helps organizations remain at the top of quality [6], [7], [8]. Real-world examples, mostly learned from the studies and literature depict successful FMEA's implementations. These specific cases illustrate that companies in different industries such as the manufacturing, healthcare, cars and the service sector are already reaping the benefits of the FMEA tool which is used to implement process improvements as well as constantly improving the quality of the product. The write up in our survey discloses also the fact that FMEA is overlapping certain quality managing techniques like Six Sigma and TQM [9], [10], [11], [12]. Practitioners in this area have extensively considered how these techniques go hand in hand with FMEA. It therefore offers organizations with the best approach which combines both continuous improvement and recognition of industry standards [13], [14], [15].

Besides, this literature suggests the FMEA application in conjunction with the ISO9001 to exemplify the contribution it makes to quality system standard around the world. The conversation further deals with the different scenarios of how the FMEA can be used, including its principles within lean manufacturing processes as well as its significance in a multiplicity of industries/sectors [16].
Conclusively, this literature review furnishes available data that gives a comprehensive insinuation of the fundamental concept of the

FMEA within quality management [17], [18], [19], [20], [21], [22]. Through combining findings from scholarly contributions and what is done in reality, the survey will be our starting point that will facilitate for subsequent sections to expound FMEA's strategies for process enhancement in this research.

3 Methodology

In this part of FMEA basic structure is described, and process of analysis is presented by using MCDM methods also in an organized form.

3.1 Failure Modes and Effects Analysis (FMEA) Method

To delve into the strategies for process enhancement using Failure Modes and Effects Analysis (FMEA) as a key component of quality management, it is essential to understand the methodological approach and the mathematical model employed in the application of FMEA [23], [24]. This section outlines the steps involved and the mathematical foundation that underpins the systematic risk assessment and improvement strategies offered by FMEA (in Fig.1).

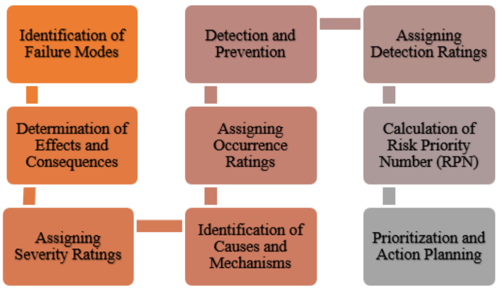

Figure 1 The proposed framework steps

The concepts related to FMEA methodology are as follows [25]:

Customer: Individuals or entities impact by a specific type of error.
Error Type: Failure to meet customer needs and expectations; the product or process fails to perform the desires function adequately or at all.
Reason for Error: The factor responsible for causing a specific type of error.
Error Effect: Situations that may lead to customer dissatisfaction.
Existing Controls: Activities conducted during the FMEA study to prevent errors from occurring and reaching the customer.
FMEA Element: Topics examined within the FMEA study.
Emergence: The likelihood of a specific error occurring during the product's known lifespan.
Detection: The effectiveness of existing controls in preventing errors from reaching the customer.
Weight: The assessment of the impact of the error's effect on the customer.
Risk Priority Number: A value obtained by multiplying the severity, occurrence, and detection ratings assigned to each failure mode.

$$RPN = Severity * Occurrence * Detection \quad (1)$$

Criticality: The multiplication of the occurrence of the error by the likelihood that the error can be detected [26] , [27].

3.1.1 Objectives of FMEA

The primary objective of the FMEA technique is to analyze potential types of errors in both the product and the process, examining their impact on the customer and assessing their associated level of risk. The aims also include the prevention of potential errors by identifying them before they manifest in the product or process. Additionally, FMEA aims to scrutinize the design characteristics of the product concerning its manufacturing and assembly processes, ensuring alignment with customer expectations. Once potential error types are identified, corrective measures are implemented to prevent their occurrence, thereby reducing the likelihood of errors and contributing to the overall product development [28], [29].

3.1.2 Process steps of FMEA

The main purpose of FMEA is to identify possible failure modes of a system or process, analyze the effects and identify measures to reduce the risks associated with failure modes. When performing an FMEA, risks are prioritized according to defined criteria and actions are taken starting with higher priority failure modes. The process of performing an FMEA consists of 10 steps, which are summarized in Figure 2 [30], [31], [32].

3.2 Application of Muti-Criteria Decision - Making techniques to FMEA

Multi-Criteria Decision-Making (MCDM) techniques can be applied to FMEA (Failure Mode and Effects Analysis) analysis to enhance decision-making by considering multiple criteria simultaneously [33], [34], [35], [36].

Here's a step-by-step guide on how to apply MCDM techniques to FMEA:

Step 1: Identify Decision Criteria

Identify the criteria that are important for evaluating failure modes in your FMEA. These criteria could include severity, occurrence, detectability, cost of prevention, impact on safety, impact on production, etc.

Step 2: Assign Weights to Criteria

Assign weights to each criterion based on their relative importance. The weights reflect the significance of each criterion in the decision-making process.

Step 3: Evaluate Failure Modes

For each failure mode identified in the FMEA, assess its performance on each criterion. You can use a scoring system or qualitative assessment to evaluate severity, occurrence, detectability, etc., for each failure mode.

Step 4: Normalize Scores

Normalize the scores for each criterion to ensure they are comparable. This is particularly important if the scales of the criteria are different. Normalization ensures that each criterion contributes equally to the decision-making process.

Step 5: Apply MCDM Technique

Choose an appropriate MCDM technique to integrate the normalized scores across criteria and rank the failure modes. Some commonly used MCDM techniques include:

- MULTIMOORA method)
- Fuzzy GRA
- MABAC with FMEA,

Step 6: Rank Failure Modes

Rank the failure modes based on the aggregated scores obtained from the MCDM technique. The higher the score, the higher the priority for addressing that failure mode. This is a great help in terms of specifying the mitigating activities and ensuring an adequate use of resources.

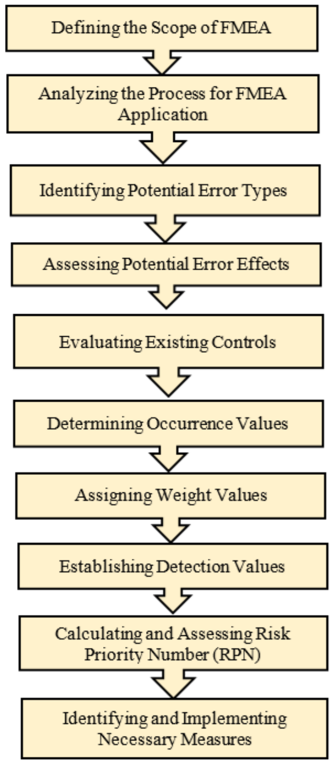

Figure 2 The FMEA process steps

Step 7: Decision-Making

Use the ranked list of failures as a basis to identify areas requiring risk avoidance measures. Attention should be centered on major SMFs that include potential consequences and frequency of occurrence.

With the application of MCDM method to FMEA analysis, you will be able to make multi-criteria evaluation and prioritize failure modes, which would result in the more informed decisions and more effectiveness in risk management. Each MCDM technique will apparently have its own advantages and disadvantages, so you will need to apply the most suitable technique based on the incident as well as your FMEA analysis.

3.2.1 MULTIMOORA

MULTIMOORA method includes, in its sequence, several stages, and there is no strict math formula during that, however, the mathematical expressions that are involved in the whole process are described.

Define or normalize the matrix X of n×m dimensions, where m is the number of alternatives, and n is the number of criteria. Normalize the as each one is in a comparable scale. This can be obtained by different normalization methods like the min-max normalization, z-score normalization, or decimal scaling.

Assign weights to the candidates. Let $w = (w_1, w_2, \ldots, w_n)$ be the vector that describes the relative significance of each criterion. Generally, the weights employed although can be determined subjectively, through expert opinion or analytically by methods such as the Analytical Hierarchy Process (AHP) and the Analytical Network Process. Compute the performance ratio for each alternative by ratio analysis. Undefined

$$R_i = \frac{\sum_{j=1}^{n} w_j x_{ij}}{\sum_{i=1}^{m}\sum_{j=1}^{n} w_j x_{ij}} \quad (2)$$

this is where x_{ij} stands for the normalized value of alternative i on criterion j and w_j is the weight assigned to criterion j. Prolong the ratio analysis to the string multiplicative form.

$$S_i = \prod_{j=1}^{n} R_{ij} \quad (3)$$

here R_{ij} composed of the proportion between alternative i and criterion j computed in prior stage. The alternatives being ranked will be the ones with the best scores S. The highest rated alternative is viewed as the best choice. These expressions are indeed the essential mathematical formulas in the MULTIMOORA approach. Nonetheless, the particular execution could be diversely affected using the particular subject and the decision-maker's preferences.

3.2.2 Fuzzy GRA

The Fuzzy GRA (Fuzzy Grey Relational Analysis) approach consisting of fuzzy logic is one of the extensions of Grey Relational Analysis (GRA) that deals with imprecision and vagueness in decision making. GRA is a tool for determining the relative proximity of different alternatives as to their criteria measure results. Normalize the matrix X, with m alternatives and n criteria, into a base matrix. It can be done via using different fuzzy normalization approaches, for example, max-min and centroid method, in order to ensure the equivalence and compatibility of all the criteria. Develop the fuzzy grey relational coefficients between the reference alternative (which may be the best or worst situation) and each alternative i in relation to all of the criteria to be considered. Consider X as the reference option with asterisk. Let x* denote the reference alternative. The fuzzy grey relational coefficient ξ_i) between alternative i and x* for criterion j is typically calculated using a formula like:

$$\xi_i^j = \frac{min\left(\mu^*\left(x_j^*\right), \mu_i(x_{ij})\right) + \rho.max\left(\mu^*\left(x_j^*\right), \mu_i(x_{ij})\right)}{max\left(\mu^*\left(x_j^*\right), \mu_i(x_{ij})\right) + \rho.min\left(\mu^*\left(x_j^*\right), \mu_i(x_{ij})\right)} \quad (4)$$

where $\left(x_j^*\right)$ and $\mu_i(x_{ij})$ represent level of fuzzy membership of an alternative with respect to x* and alternative i with respect to criterion j, and ρ is the distinguishing coefficient. Compute the fuzzy grey relational grade GRi for each alternative by aggregating the fuzzy grey relational coefficients across all criteria. This can be done using aggregation methods such as the arithmetic mean, geometric mean, or ordered weighted averaging (OWA).

$$GR_i = \frac{1}{n}\sum_j^n \xi_i^j \quad (5)$$

Rank the alternatives based on their fuzzy grey relational grades GR_i. Higher GR_ivalues indicate higher similarity to the reference alternative and thus better performance.

In the above formulas, x_{ij} represents the value of alternative i on criterion $\mu^*\left(x_j^*\right)$ represents the membership grade of the reference alternative on criterion j, and $, \mu_i(x_{ij})$ represents the membership grade of alternative i on criterion j. The distinguishing coefficient ρ adjusts the sensitivity of the grey relational coefficients to differences between alternatives.

3.2.3 MABAC

The MABAC (Multi-Attributive Border Approximation area Comparison) method is a multi-criteria decision-making (MCDM) approach that aims to rank alternatives based on their performance across multiple criteria. Normalize the decision matrix X of size m×n, where m is the number of alternatives and n is the number of criteria. For the sake of the comparison, this stage of process makes all the parameters uniform. Z-score normalization and min-max normalization are examples of nornalization techniques. Create the criteria scaling to indicate which criteria are more significant. Consider the vector of weights $w = (w_1, w_2, \ldots, w_n)$. In which w_j represents the weight of criterion j possibly provided by expert judgment, analytical methods(for example, Analytic Hierarchy Process), or stakeholder preferences. Provide a definition preference function $P(x_{ij})$for all criterion j and alternatives i. The preference function shows how much satisfaction or preference for specific criterion value. It may appear in different shapes, for instance, as a linear, triangle, Gaussian, or trapezoidal function, which B_{ij} is determined by the type of the criteria and the way in which the decision-maker prefers to solve the problem.

$$B_{ij} = \frac{min\left(P(x_{ij}),P(I_j)-P(x_{ij})\right)}{max\left(P(x_{ij}),P(I_j)-P(x_{ij})\right)} \quad (6)$$

where $P(I_j)$ is defined as the ideal value of criterion j(usually the maximum value or minimum value, depending on the type of the criterion - maximization or minimization). Establish the ideal solution and anti-ideal solution for each index by weighting them. The value ofI_j^+, the best possible value of criterion j, is the positive ideal solution of the criterion, and the value of I_j^-, the worst possible value, is the negative one. Such a result can be achieved by taking the best and the worst of all criteria and for every alternative. Get the MABAC score of alternative i, S_i if, by summing the borderline approximations produced on each criterion. Different aggregation functions like weighted sum as well as weighted product can be utilized in order to achieve this.

$$S_i = \sum_{j=1}^{n} w_j . B_{ij} \quad (7)$$

Rearrange the choices from less effective (MABAC score = v) to most effective(MABAC score = S_i). The higher score show that alternative has superior performance, thus the alternative with the highest score will be ranked first while the second highest score will be ranked after that. These mathematical formulations unveil for the user MABAC main moves during multi-criteria decision-making. It is an organized tool that helps in the examination and the ranking of alternatives based on their capacity to perform very well considering a number of criteria.

3.3 Improving decision making by combining FMEA with MULTIMOORE, Fuzzy GRA and MABAC

FMEA (Failure Mode and Effects Analysis) stands as the systematic approach in recognizing the probable failure modes that a system can have, the effects if they occur, and the likelihood of their happening now with our preventive controls. This is one of the most critical methods that industries like the food and beverage, automotive, aerospace, health care, etc utilize to improve manufacturing processes, products and systems. Taking into account FMEA and MCDM together enables making clear-cut decisions possibly in situations consisting various failure modes or risks assessments and at the very same time where numerous factors or criteria should be taken into consideration. Here's given the combined MCDM within FMEA analysis in below:Here's given the combined MCDM within FMEA analysis in below:

1. Identify Attributes or Criteria: Specify those key characteristics that are actually important in assessing failure modes. These factors can be represented by at least occurrence, severity, detectability, prevention costs, impact on safety, impact on productivity, etc.

2. Assign Weightings: Assign weights to each attribute based on their relative importance. This weighting reflects the significance of each criterion in the decision-making process.

3. Evaluate Failure Modes: For each failure mode identified in the FMEA, assess its performance on each criterion. Scoring system or qualitative assessment evaluates severity, occurrence, detectability, etc., for each failure mode.

4. Calculate Scores: Multiply the scores of each failure mode by the assigned weights for each criterion. This gives a weighted score for each failure mode on each attribute.

5. Aggregate Scores: Aggregate the weighted scores across all attributes to obtain a total score for each failure mode. This represents the overall evaluation of the failure mode considering all criteria.

6. Ranking and Prioritization: Rank the failure modes based on their total scores. The higher the score, the higher the priority for addressing that failure mode. This helps in prioritizing mitigation efforts and allocating resources effectively.

7. Decision-Making: Utilize the ranked list of failure modes to inform decision-making regarding risk mitigation strategies. Focus on addressing high-priority failure modes first, considering their potential impact and likelihood of occurrence.

By integrating MCDM with FMEA, you can systematically assess and prioritize failure modes based on multiple criteria, enabling more informed decision-making and proactive risk management.

4 Case Study

The company strives to enhance its competitiveness by focusing on the quality and production efficiency of its products. Cables, being crucial components influencing the performance of military vehicles, demand durability and world-class production standards. Customer companies subject their suppliers to rigorous inspections, monitoring their endeavors to achieve the desired quality. Consequently, the company is dedicated to attaining production quality and ensuring the effective operation of its established quality management system. This study aims to identify, systematize, and illustrate the advantages of the cables manufactured by the company. An examination is conducted on the cables returned by customers for correction, with a focus on understanding the reasons for the returns. Some of the customer companies cables are subject to returns, and the company consistently faces challenges with these cables, resulting in decreased factory efficiency. By pinpointing the reasons for returns, the identified problems have been addressed, and a systematic solution has been devised and documented.

4.1 Determination of Emergence, Severity and Detection Values

While calculating the emergence, severity and detection values, all customer returns were examined. The emergence rating table was used for the selected product types while the average value was determined, the Severity rating table was used while determining the determination value. The scoring system is made with a rating of 1-10 (in Table 1-6).

Table 1: Statement rating table

Probability of Emergence	Degree	Probability of Error
Hardly ever	1	<1:20.000
Low	2	1:20.000
	3	1:10.000
Middle	4	1:2.000
	5	1:1.000
	6	1:200
High	7	1:100
	8	1:20
Very High	9	1:10
	10	1:2

Table 2: Occurrence probability rating table

Cable Code	Cable Construction Error	Adapter Error	Marking Error	Common Errors	Pinning Error	Connector Error	Socket Error	Panel Error	Retouching ErrorI	Terminal Error
125243						7				
802147						6				
113580		7			7					
W18					6		6			
801374			5			5				
W42										7
125026								6		
117529				8						
W58	6									
127584									7	

Table 3: Severity rating score table

Weight(Impact on customer)	Degree
Hardly ever	1
Low	2
	3
Middle	4
	5
	6
High	7
	8
Very High	9
	10

Table 4: Severity rating score table

Cable Code	Cable Construction Error	Adapter Error	Marking Error	Common Errors	Pinning Error	Connector Error	Socket Error	Panel Error	Retouching ErrorI	Terminal Error
125243						9				
802147						9				
113580		10			6					
W18					7		5			
801374			4			9				
W42										7
125026								4		
117529				8						
W58	7									
127584									8	

Table 5: Severity rating score table

Detectability	Degree	Detectability Possibility(%)
Very high	1	86-100
	2	76-85
High	3	66-75
	4	56-65
Middle	5	46-55
	6	36-45
	7	26-35
	8	16-25
Low	9	6-15
Almost impossible	10	0-5

Table 6: Detectability Evaluation Chart

Cable Code	Cable Construction Error	Adapter Error	Marking Error	Common Errors	Pinning Error	Connector Error	Socket Error	Panel Error	Retouching ErrorI	Terminal Error
125243						2				
802147						2				
113580		1			3					
W18					3		3			
801374			2			3				
W42										4
125026								4		
117529				3						
W58	2									
127584									3	

4.2 Analyzing with MULTIMOORA Method

In this method, the best and worst alternatives are determined for each criterion and then a score is made based on the distance of the performance of each alternative to these best and worst alternatives.

First, let's review the activities in the dataset and their criteria (in Fig.3):

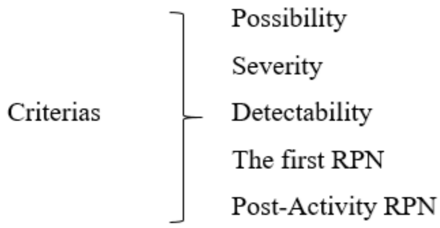

Figure 3 FMEAS's criteria

Activities:

1. Documentation of approval of connector strength before shipment
2. Pin control for each cable
3. Updating on a common server for everyone to notice when the picture is updated
4. Training of people who control and standardize the crimping process
5. No other material is used without customer approval
6. Pin control for each cable
7. Adding to the ones to be checked in the intermediate control
8. Making a connector check at every stage of the quality control
9. The person who makes the marking is competent to understand the technical picture
10. Adding the terminal to the technical drawing according to the branches
11. Using the desired size value tubing
12. Detecting short circuits while testing the cable
13. While measuring the length of the cable, it is done with a quality controller.
14. Using quality macaron and glue while retouching

The MULTIMOORA method steps are:

Step 1: Standardization of Data

Let's standardize the data so that the performance of each alternative for each criterion is comparable

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Step 2: Determining the Weights

Weights are determined for the criteria. However, since there is no information here about the importance of each criterion, we will assume the weights are equal.

Step 3: Calculating Performance Scores

We will calculate performance scores for each alternative.

Step 4: Sorting

We ranked the alternatives according to their performance scores and listed the applied steps:

Step 1: Standardization of Data

Let's calculate the standardized values of the data for each criterion.

Step 2: Determining the Weights

We considered the weights equal: $\frac{1}{5} = 0.2$

Step 3: Calculating Performance Scores

The performance scores calculated for each alternative (in Table 7).

Table 7: Calculating the performance scores for each alternatives

Cable Code	Possibility	Severity	Detectability	The first RPN	Post-activity RPN	Total Score
125243	7	9	2	126	42	0.2*(7+9+2+126+42) =37.4
802147	6	9	2	108	40	0.2*(6+9+2+108+40) =33

Step 4: Ranking

Let's list the alternatives according to their performance scores.

Ranking (from highest score to lowest score):

1. (125243); 2. (113580); 3. (127584); 4. (117529); 5. (W18); 6. (802147); 7. (W58); 8. (801374); 9. (125026); 10. (W42); 11. (125026); 12. (802147); 13. (113580); 14. (W42)

This ranking is based on the performance of each alternative evaluated according to the MULTIMOORA method.

4.3 Calculation and Evaluation of the Risk Priority Number (RPN)

The variables of RPN are calculated with FMEA ratings for severity, detection, and Probability tables, where numbers one and ten represent the lowest and most significant risk factors, respectively. The RPN values range from 1 to 1000. The absolute best to absolute worst RPN value is ranges from 1 to 1000. A FM with such a greater RPN is more important and has a greater priority.

The risk priority coefficient (RPC) obtained with multiplying the emergence value, severity value and detection values that was calculated for each selected error type (in Table 8).

Table 8: RPN Evaluation Chart

Cable Code	Cable Construction Error	Adapter Error	Marking Error	Common Errors	Pinning Error	Connector Error	Socket Error	Panel Error	Retouching Error	Terminal Error
125243	0	0	0	0	0	126	0	0	0	0
802147	0	0	0	0	0	108	0	0	0	0
113580	0	70	0	0	126	0	0	0	0	0
W18	0	0	0	0	126	0	90	0	0	0
801374	0	0	40	0	0	135	0	0	0	0
W42	0	0	0	0	0	0	0	0	0	196
125026	0	0	0	0	0	0	0	96	0	0
117529	0	0	0	192	0	0	0	0	0	0
W58	84	0	0	0	0	0	0	0	0	0
127584	0	0	0	0	0	0	0	0	168	0

The distribution of RPN values defined with error types such as cable construction error, adapter error, marking error, common errors, pinning error, connector error, socket error, panel error, retouching error and terminal error (in Figure 4). For each type of RPN error, we can analyze the most frequently encountered risk situations and the least frequently occurring risk situations from the distribution chart.

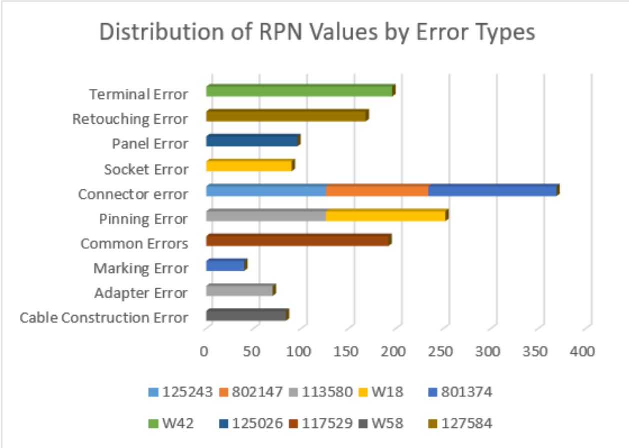

Figure 3: Distribution of RPN Values by Error Types

Probabilities of specific activities, risk severities, detectability levels and recommended activities are given for each cable code in the data set. First of all, RPN for each cable code calculated using Fuzzy GRA and MABAC methods.

1. Fuzzy GRA (Grey Relational Analysis): We determined RPN values for each activity by calculating the similarity levels of the data.
2. MABAC (Multi-Attribute Border Approximation area Comparison): We considered RPN values by evaluating activities in terms of probability, risk severity and detectability.

4.3.1 Calculating RPN with using Fuzzy GRA Method

For Fuzzy GRA analysis, the steps of normalizing the data obtained and calculated the similarity degrees. The degree of similarity of each activity to other activities done.

Step 1: Normalization of Data

Let's normalize the data by dividing each criterion by the maximum value. For example, the maximum value for the probability criterion is 8. Let's normalize the data according to this value)in Table 9).

Step 2: Fuzzy GRA Calculation

To calculate Fuzzy GRA, we calculated the degree of similarity between each activity and other activities. For this, we took the absolute value of the difference between the values of other activities for each criterion for each activity and the same criterion. We calculated the degrees of similarity by multiplying these differences respectively by a certain factor (usually 0.5) in Table 10.

Table 9: Normalization of Data

Cable Code	Possibility	Severity	Detectability
125243	7/8	9/10	2/4
802147	6/8	9/10	2/4
	5/8	8/10	1/4
113580	7/8	10/10	1/4
	6/8	7/10	2/4
W18	6/8	7/10	3/4
	6/8	5/10	3/4
801374	5/8	9/10	3/4
	5/8	4/10	2/4
W42	4/8	6/10	2/4
125026	6/8	4/10	4/4
117529	8/8	8/10	3/4
W58	6/8	7/10	2/4
127584	7/8	8/10	3/4

Next, we will calculate the degrees of similarity by multiplying each difference by a certain factor.

Table 10: Differences between probability criterion of other activities

Activity	Possibility	Severity	Detectability
802147	1/8	0/10	0/4
113580	1/8	1/10	1/4
W18	1/8	1/10	2/4
801374	2/8	0/10	1/4
W12	3/8	1/10	1/4
125026	1/8	5/10	2/4
117529	1/8	1/10	1/4
W58	1/8	0/10	0/4
127584	0/8	1/10	1/4

Step 3: Interpreting the Results

Degrees of similarity are interpreted and relationships between activities are determined. A higher degree of similarity means more similarity. By completing these steps, we can obtain Fuzzy GRA analysis results. However, in order to perform the full analysis, to calculate the differences and similarity levels of each activity and other activities between all criteria.

4.3.2 4.4.2 Calculating RPN with using MABAC Method

Let's analyze each activity in your data set with the MCDM method. First, we will evaluate each activity in terms of probability, risk severity and detectability using the MABAC (Multi-Attribute Border Approximation area Comparison) method. Next, we prioritized each activity.

Step 1: Calculating MABAC Scores

Let's consider a simplified example of applying MABAC to FMEA analysis for a manufacturing process. We focused on three criteria: severity, occurrence, and detectability. We used a scale of 1 to 10 for each criterion, with 10 being the highest importance or severity.

Identify Attributes and Assign Weightings

- Severity weight = 0.4
- Occurrence weight = 0.3
- Detectability weight = 0.3

Step 2: Evaluate Failure Modes

Let's consider two failure modes: "Machine Breakdown" and "Material Shortage."

Machine Breakdown:

- Severity: 9
- Occurrence: 7
- Detectability: 6

Material Shortage:

- Severity: 7
- Occurrence: 8
- Detectability: 5

Step 3: Calculate Scores

For Machine Breakdown:

$$Severity\ Score = (9 * 0.4) = 3.6 \quad (8)$$
$$Occurence\ Score = (7 * 0.3) = 2.1 \quad (9)$$
$$Detectability\ Score = (6 * 0.3) = 1.8 \quad (10)$$
$$Total\ Score = (3.6 + 2.1 + 1.8) = 7.5 \quad (11)$$

For Material Shortage:

$$Severity\ Score = (7 * 0.4) = 2.8 \quad (12)$$
$$Occurence\ Score = (8 * 0.3) = 2.4 \quad (13)$$
$$Detectability\ Score = (5 * 0.3) = 1.5 \quad (14)$$
$$Total\ Score = (2.8 + 2.4 + 1.5) = 6.7 \quad (15)$$

Step 4: Ranking and Prioritization

- Machine Breakdown total score = 7.5
- Material Shortage total score = 6.7

So, based on this analysis, "Machine Breakdown" is prioritized over "Material Shortage" for mitigation efforts. With this prioritized list, the team can now focus on addressing the causes and consequences of machine breakdowns, such as implementing preventive maintenance schedules, upgrading equipment, or improving monitoring systems.

This numerical example demonstrates how MABAC can be applied to FMEA to systematically evaluate and prioritize failure modes based on multiple criteria, facilitating more informed decision-making in risk management (in Table 11).

Table 11: Activity's MABAC Score

Cable Code	Possibility	Severity	Detectability	Post-Activity RPN	MABAC Score
125243	7	9	2	126	101.5
802147	6	9	2	108	87.5
	5	8	1	40	27.5
113580	7	10	1	70	55.5
	6	7	2	84	70.5
W18	6	7	3	126	104.5
	6	5	3	90	74.5
801374	5	9	3	135	110
	5	4	2	40	32.5
W42	4	6	2	48	37.5
125026	6	4	4	48	39
117529	8	8	3	192	155.5
W58	6	7	2	84	70.5
127584	7	8	3	168	136.5

Step 2: Determining the Order of Priority

Let's prioritize activities according to MABAC scores:

1. 117529 (155.5) ; 2. 127584 (136.5); 3. 801374 (110.0); 4. W18 (104.5); 5. 125243 (101.5); 6. 802147 (87.5); 7. W58 (70.5); 8. 113580 (55.5); 9. 125026 (39.0); 10. W42 (37.5)

In this way, the priority order of each activity was determined. Starting with the highest priority activity, the order is as above.

Variable types of data included in the proposed model are given as cable code, possibility, severity, detectability, the first RPN, recommended activities and post-activity RPN (in Table 12).

In RPN value calculations made in the previous stages, error types with high risk levels determined. The preventive activities to be taken discussed and the FMEA form is formed and the RPN values again examined. It can be understood from the decrease in the RPN values where the risk reduced with the preventive activities taken in the Appendix-2.

5 Conclusion

The initiation of FMEA application involved a comprehensive examination of the target process. This encompassed scrutinizing customer complaints and quality control records to pinpoint existing issues. Current and potential problems were systematically identified, and an evaluation of existing controls was conducted. The causes and effects of errors were elucidated, followed by the determination of Risk Priority Number (RPN) values on the FMEA form. Subsequent to these assessments, system improvements were outlined. Post-improvements, a reevaluation of risk analysis took place, gauging the efficacy of the implemented enhancements.

Table 12: Table of the first and Post Activity RPN for each Cable Code

Cable Code	Possibility	Severity	Detectability	The first RPN	Recommended Activities	Possibility	Severity	Detectability	Post-Activity RPN
125243	7	9	2	126	Documentation of approval of connector strength before shipment	6	7	1	42
802147	6	9	2	108	Pin control for each cable	5	8	1	40
	5	8	1	40	Updating on a common server for everyone to notice when the picture is updated	2	8	1	16
113580	7	10	1	70	Training of people who control and standardize the crimping process	6	8	1	48
	6	7	2	84	No other material is used without customer approval	2	7	1	14
W18	6	7	3	126	Pin control for each cable	6	6	1	36
	6	5	3	90	Adding to the ones to be checked in the intermediate control	5	5	2	50
801374	5	9	3	135	Making a connector check at every stage of the quality control	5	8	1	40
	5	4	2	40	The person who makes the marking is competent to understand the technical picture	5	4	2	40
W42	4	6	2	48	Adding the terminal to the technical drawing according to the branches	3	6	1	18
125026	6	4	4	96	Using the desired size value tubing	6	4	2	48
117529	8	8	3	192	Detecting short circuits while testing the cable	7	6	1	42
W58	6	7	2	84	While measuring the length of the cable, it is done with a quality controller.	6	6	1	36
127584	7	8	3	168	Using quality macaron and glue while retouching	6	8	1	48

The processes facilitated in their utilization in future projects, to establishing a corporate memory for the company. This initiative elevated the reliability of the company's products and services, so it enhanced the competitive process, and bolstered customer satisfactions. The company under- went a positive transformation in image and experienced of their reduction in warranty costs. Furthermore, this approach significantly contributed to the accumulation of engineering knowledge. It is imperative to underscore the continuous need for controls and evaluations to sustain the achieved improvements over time.

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APPENDICES

APPENDIX-1

	POSSIBLE FAULT TYPES
CABLE	Short and long cutting of the length of the cable due to carelessness in dimensioning of cable lengths
	The cables are irregular due to the lack of touch-up on the back of the socket, the back of the socket and the branch or excessive contamination of the surface of the drug.
	If the insulation of thick cables such as 50mm'2 is not fully opened, the cables do not have electrical conductivity when plugged into the contacts.
	Incorrect separation and knitting of cable branches
	Cable insulation is damaged, torn or burned
	Cable ends not opening properly, damaging or breaking the wires during end opening operation
ADOPTER	Damaged minted adapter
	Adapters don't get bored well, turns on
	Tired by holding the wrong tooth to the adapter
	Drawing the adapter during twisting
	Usage of wrong adapter

BRANCH AND SOCKET BACK COVER	Incorrect branch directions due to the shrinkage of the branches by attaching them to the cable without paying attention to their directions.
	Incorrect heating of the branch and SBC by installing them without paying attention to the part numbers
	The branch form is shrunk incorrectly due to not applying heat evenly while shrinking the branch or SBC.
	The branch or SBC cable does not fully cover the surface and openings are visible
	Later opening and spacing of the adhesive applied area as the branch or SBC shrunk surface is not well cleaned of oil and dust
	In the second use of the branch or SBC, there are tears in the branch branches or deformities on the surface.
	Improper heating of the branch or SBC, deformities
MARKING	Label bursting or fraying while heating
	Using marking on incorrect cable branches
	Incorrect shrinkage dimensions of the marking sleeves on the cable
	Marking and protective sleeves are cut to wrong dimensions and irregularly. Irregularly cut protective tubes wrap the uneven cable while shrinking.
	The reading directions of the marking sleeves are shrunken by inserting them in the wrong direction.
	Incomplete or incorrect branding, lack of transparency
	The marking is not read well or the label is slipping due to improper heat applied to the label.
	The label is faint
	Not heating the label
COMMON	Incomplete or damaged material
	There is a chassis in the cable
	Throwing the cable rope irregularly, not burning it or not throwing it at all
	Inserting material upside down
	Opening or not opening the silicone-medicine
	Incorrect material installation
	Incorrect taping
	Insulation weakness
PINS RINGS	Contacts coming off the cable due to not tightening the contacts in the appropriate tightening range
	Breakage and cracking of contacts due to not tightening the contacts to the appropriate torque
	Oblique tightening of the contacts due to not holding the contacts properly when inserting them into the cable (Pin crooked)
	Conductive wires coming out of the contact slot due to cable conductors not being fully inserted into the contacts
	Installing cables with cross-sections that are not suitable for contacts
	Contacts not tightened within the appropriate tightening range
	Not inserting empty connector contacts, not fully seated contacts
	Improper tightening of the shoe with the wrong tool and damage to the shoe
	Visibility of the conductor through the hole of the cable lug
CONNECTOR	Incorrect connector installation
	Do not insert empty pins
	Damaged or damaged connector
	Incorrect connector angle
	Contacts not being inserted into the connector in accordance with the letter coding, incorrect connection
	Unbalanced insertion of contacts backwards into the connector
	Incorrect or no gasket installed on the connector
	Cables are messy as a result of messy insertion of cables as a result of messy insertion of contacts into the connector
	Incomplete connection or wrong bridge
	Wire coming out while terminating the shield, faulty termination
	Connection skipping problem

SOLDERING	Due to the high amount of paste used during soldering, it may cause electrical conductivity and create a short circuit in the system.
	Poor soldering due to non-homogeneous soldering and use of less solder, resulting in breakage of the soldered area.
	Solder overflow on the surface due to the use of too much solder
	Electrical conductivity occurs between contacts due to solder overflows not being cleaned properly.
	The contacts are soldered crookedly or cannot be inserted into the connector slot due to the soldering being done without properly placing the cables into the contacts.
	Not placing tubing on the solder joints in cable joints or not covering the soldered area completely, causing chassis formation between the cables.
	Cable not completing the circuit due to solder breakage
	Faulty solder sleve heating
	No soldering
	Long or short solder sleeve opening length
	Wire coming out from the soldered area
RUBBER SOCKET	Forgetting to install the washer in male and female sockets
	Pins not fully tightened
	Incorrect installation of female and male rubber sockets
	Incorrect installation of pins of male and female sockets
	Reverse insertion of pins into socket or connector
	Broken pins
	Incorrect or not connected fiber
	Pins not tightened well or not at all
	Torn or damaged socket
TUBE	Incorrect heating of tubing. Mistaken use of tubing with similar measurements interchangeably
	Deterioration of the tubing surfaces due to improper heating of the tubing and excessive heat deforming the surface.
	Excessive narrowing and widening may occur on the surface of the tubing due to heat not being applied equally to the surface while shrinking the tubing.
	Presence of holes, cracks and scratches on the surface of the tubing
	Due to the lack of protective tubing on the connector contacts, there is a ground between the contacts.
	Smearing glue on the tubing surfaces and seeing the sanded surfaces on the cable
	Damage to the protective tubing of the contacts or conductive wires coming out by piercing the tubing
	There are errors in the joints of the tubes and they are added incorrectly.
	Under or over taping
	Not inserting or heating the tubes
PANEL	Bolts not properly tightened or installed during box assembly
	The cables coming to the terminal are not connected in accordance with the diagram
	Wrong connection made
OPERATION ERROR	Observation in the application of end components or the cable not coming out sufficiently or not visible at the head and back parts
	Not shaping the cable properly
RETOUCH	Opening cable touches
	No retouching of the cable
TERMINAL	Use of wrong material due to installation of terminals without checking the hole diameters
	Using the wrong material without checking terminal colors
	Terminals coming out of the cable due to not tightening the terminals to the appropriate cross-sections
	Breakage and cracks due to incorrect tightening of the terminals and not tightening the material with the appropriate torque
	Improper tightening of terminals with the wrong tool

APPENDIX-2

Cable Code	Failure types	Effects of Failure	Reason of Failure	Actual Controls
125243	Damage and dents in the connector	Low quality material; short cable life	Dropping or hitting the connector	Care should be taken with the connector during production, control and transportation stages.
802147	Contacts not attached to the connector according to the letter coding	Failure to establish a connection between pins.	Operator mistake	Looking at pins if there's pin control
	Producing a product according to old revised technical drawing	Rejection of the product	Not tracking revision status	R&D's drawing update when the cable is revised
113580	Disconnection of the terminal	Coming out of copper cables	The size and profile of the crimping feet are not correct	Checking crimping when closing the cable
	Use of wrong materials without customer request	Rejection of the product, loss of image and quality points	Wanting to use other materials instead of materials that are not in the warehouse	The production manager detects the missing material and requests it from the warehouse.
W18	Pins are left behind	Loss of contact in the connector	Damage of the socket	Looking at pins if there's pin control
	Finding a tear in the gasket	Pins coming out	Not inserting empty connector contacts	Visiual control
801374	Incorrect connector installation	Rejection of the Product	Having a lack of follow-up	Interim control by looking at the technical drawing
	Reverse of label connection	Performens Kriterlerinin Sağlamaması	Lack of competence of the marking employee	Approval of the spelling of the label should be taken by only marking person.
W42	Wrong terminal usage.	Reverse generation of branches	Installing terminals without checking the hole diameters	Checking according to branch codes
125026	Bolt ends on the cover remaining in the nut	The lid does not fit properly on the box	Improper heating of macarons	Interchangeable use of nearby measurement values
117529	Short circuit at the disconnected end of the branch	Incorrect connections in the cable	Incorrect alignment of pins	Letter controlling at pins
W58	Incorrect Branch Size	The cable does not fit the installation	Carelessness in measuring cable lengths	Measuring of cable size initially
127584	Removing Adhesives from Macarons	Mistakes in the macaroni attachments	Retouching carelessly	Checking after the macaron is heated

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