



**DECISION MAKING FOR RISK EVALUATION: INTEGRATION
OF PROSPECT THEORY WITH FAILURE MODES AND EFFECTS
ANALYSIS (FMEA)**

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Abstract:	

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DECISION MAKING FOR RISK EVALUATION: INTEGRATION OF PROSPECT THEORY WITH FAILURE MODES AND EFFECTS ANALYSIS (FMEA)

Abstract

Purpose: The aim of the present study is to overcome some of the limitations of the FMEA method by presenting a theoretical base for considering risk evaluation into its assessment methodology and proposing an approach for its implementation.

Design/methodology/approach: Fuzzy AHP is used to calculate the weights of the likelihood of occurrence (O), severity (S) and difficulty of detection (D). Additionally, the Prospect Theory-based TODIM method was integrated with fuzzy logic. Thus, fuzzy TODIM was employed to calculate the ranking of potential failure modes according to their RPNs. In order to verify the results of the study, in-depth interviews were conducted with the participation of industry experts.

Findings: The results are very much in line with Prospect Theory. Therefore, practitioners may apply the proposed method to FMEA. The most crucial failure mode for a firm's attention is furnace failure followed by generator failure, crane failure, tank failure, kettle failure, dryer failure, and operator failure, respectively.

Originality/value: The originality of this paper consists in integrating Prospect Theory with the FMEA method in order to overcome the limitations naturally inherent in the calculation of the FMEA's Risk Priority Numbers (RPNs).

Keywords: Prospect Theory; Failure Modes and Effects Analysis; Fuzzy AHP; Fuzzy TODIM; Risk Priority Number

1. Introduction

The supply chain activities involve various potential and known failures, and risks (Mangla et al., 2015). Especially in engineering, failure modes and effects analysis (FMEA) is a well-known and commonly used technique, identifying and eliminating potential and known failures. The key objective of the FMEA is to evaluate the risk of potential failure modes and to prioritize failures by identifying the appropriate corrective actions.

FMEA enhances the design of products and processes by identifying potential failures in order to take preventive measures in the early stages (Teng, 1996). It is commonly used in planning, determining, and removing actual or potential failures, troubles, and errors in processes, designs, and services before these reach the customer (Stamatis, 1995). FMEA represents a strong and authenticated structure for engineers to demonstrate their personal

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4 experience with regard to “1) what might go wrong?, 2) what might cause it to go wrong?,
5 and 3) what effects would it have?” (Sankar & Prabhu, 2001).
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8 Traditionally, for risk evaluation, risk priority numbers (RPN) are used in FMEA
9 assessments. RPNs are calculated by multiplying the severity, occurrence, and detection of
10 potential errors/failures. In this line, severity refers to the assessment of seriousness’ level,
11 an occurrence is related to the likelihood for a specific cause to occur, and detection considers
12 the ability to detect a problem (Dong, 2007).
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15 Although FMEA is one of the most important and effective early preventative action systems
16 in terms of risk evaluation and assessment, some limitations are commonly highlighted in the
17 literature. In this study, limitations are analyzed and solution methods are suggested for four
18 limitations, summarized as follows (Braglia, Frosolini, & Montanari, 2003; Yang, Bonsall,
19 & Wang, 2008; Wang, Chin, Poon, & Yang, 2009; Gargama & Chaturvedi, 2011; Kutlu &
20 Ekmekcioglu, 2012; Liu, Liu, & Liu, 2013):
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- 23 1) Because of the hidden risk implications, the similar value of RPN can be obtained by
24 different O, S, and D combinations, although the values of their risk factors are
25 completely different. For instance, for two different failure modes, the values of 4, 6,
26 3 and 1, 8, 9 for O, S, and D, respectively, have an identical RPN value, 72. This may
27 lead to the misdiagnosing of high-risk failures.
28
- 29 2) Another weakness is the mathematical form adopted for calculating the RPN, which
30 is strongly sensitive to variations in risk factor evaluations.
31
- 32 3) Risk factors are difficult to evaluate precisely; therefore, there is a need for linguistic
33 terms such as “Important” or “Low” to express the judgments about the three factors,
34 because such judgments cannot be exactly approximated.
35
- 36 4) The traditional FMEA assumed three risk factors as equally important, without
37 considering the relative importance of each. However, each factor may have different
38 importance ratings for different failure modes.
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41 Some studies about FMEA applications to eliminate some of these limitations are as follows:
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44 Chin, Chan, and Yang (2008) proposed a fuzzy knowledge-based system to help users
45 accomplish an FMEA analysis in order to enhance quality and reliability, appraise alternative
46 design, choose materials, and evaluate costs. In their study, Kutlu and Ekmekcioglu (2012)
47 proposed an integrated approach by employing fuzzy TOPSIS and fuzzy AHP to find O, S,
48 and D values for RPN calculation using fuzzy AHP technique to find the importance ratings
49 of risk factors, and fuzzy TOPSIS technique to find the scores of potential failure modes. In
50 their work, Hua, Hsu, Kuo, and Wua (2009) applied FMEA analysis in order to comply with
51 the European Union (EU) Restriction of Hazardous Substances. Fuzzy AHP technique was
52 employed to identify the importance ratings of the risk factors of green components, and then
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RPN was computed for each component. Tay and Lim (2006) proposed a fuzzy RPN technique and fuzzy inference techniques to overcome the weak points of the traditional FMEA approach. In comparison to the traditional ones, the fuzzy approach has two main advantages: (i) the assessments of risk factors and ranking of failure modes are managed based on experts' judgments; (ii) the assessments of risk factors are aligned with the process environment. Mangla et al. (2018) proposed the assessment of risks associated with green supply chain management for benchmarking the performance using fuzzy FMEA.

From this point of view, in order to overcome FMEA limitations, which are caused mainly by conventional risk evaluation methods, research questions for this study are structured as follows:

- What form of theoretical base is required to construct risk evaluation in FMEA?
- In view of the theoretical base mentioned in the above question, which approach should be applied?

In this study, the Fuzzy Analytic Hierarchy Process method, which is integrated with fuzzy logic due to its advantages mentioned above, was used to calculate the weights of criteria, the likelihood of occurrence (O), severity (S) and difficulty of detection (D). Then, in order to evaluate and rank the risks, the TODIM method was used. The TODIM method is a discrete multi-criteria method, based on the prospect theory of Kahneman and Tversky (1979), and the word TODIM is the Portuguese acronym for Interactive and Multi-Criteria Decision-Making (Gomes, Rangel, & Maranhao, 2009). In general, all discrete multi-criteria methods accept that decision-makers always search for the maximum global measure value for the corresponding solution; on the other hand, TODIM uses a global measurement of value calculable by the implementation of prospect theory. Furthermore, since risk factors including severity, occurrence and detection are difficult to evaluate precisely, the TODIM method was integrated with fuzzy logic; thus, for risk evaluation, in the RPN calculation, the fuzzy TODIM method is employed to perform the ranking of potential failure modes. The major contribution of this paper is the innovative approach of integrating Prospect Theory with FMEA, followed by the application of Fuzzy TODIM for the integrated prospect theory and FMEA approach.

In the following sections of this study, firstly, details of FMEA, including related literature and shortcomings, are given. After that, prospect theory is explained, and then the integration of prospect theory and FMEA is presented in detail. Then, methodology, application and results are given, respectively.

2. Failure Modes and Effect Analysis (FMEA)

FMEA was first introduced by NASA in 1963, and subsequently, in 1977, it was adopted and upgraded by Ford Motors. FMEA is used to determine the risk priority number (RPN) of the design of the product or process in order to determine the item causing most risk (Chang, Wei, & Lee, 1999). As a strong and authenticated tool for security and reliability of the products or processes, it was put into practice in a wide range of industries (Kutlu & Ekmekcioglu, 2012; Sharma, Kumar, & Kumar, 2005).

A standard FMEA involves a number of aspects: recognition of the failure modes and resultant faults, determining their chances of occurrence, determining their chances of detection, determining their severity and their consequences, measuring the risk, prioritizing the faults based on risks, acting on high-risk problems, controlling the efficiency of action, and revising the measure of the risk (Ben-Daya & Raouf, 1996; Kutlu & Ekmekcioglu, 2012).

FMEA is identified as a bottom-up approach where any complex system is divided into subsystems, which are examined to find out all potential failure modes and effects. The evaluation of FMEA is a tool used for analyzing the risks and providing information for decision-making processes. It is used in many industries such as automotive, electronics, aerospace, nuclear, healthcare, and mechanical industries (Liu, Liu, & Liu, 2013; Liu, Chen, You, & Li, 2016; Song, Ming, Wu, & Zhu, 2014).

There are likely to be multiple failure modes in any process, design, or a system. Under these circumstances, each failure mode has to be measured and ranked based on their level of risks in order to identify the high-risk failure modes with the greatest importance. FMEA identifies the ranking of the risks of failure modes using a risk priority number (RPN), which is found by multiplying a failure's likelihood of occurrence (O), severity (S) and difficulty of detection (D). Therefore, $RPN = O \times S \times D$ (Chin, Chan, & Yang, 2008). Each factor is measured between 1 and 10, in which 1 corresponds to the best, and 10 to worst. RPN is measured for each failure mode to discover the high-risk failures.

2.1. Limitations of FMEA

In the study of Liu, Liu, and Liu (2013), classification of risk evaluation methods in FMEA was presented and methods used in FMEA are categorized as multi-criteria decision-making (MCDM), mathematical programming, artificial intelligence, integrated approaches and other approaches including cost-based model, Monte Carlo simulation, minimum cut set theory, etc. According to the numerical results of their study, 22.5% of the FMEA studies use different kinds of MCDM methods and 11.25% used integrated approaches, which means more than one-third of these methods are utility theory-based.

In these utility theory-based MCDM methods or integrated approaches, marginal change in gain or loss are considered equal, which is another weakness of risk evaluation in FMEA. However, in real situations, in which the decision-making process is under risk, this marginal effect shall not be equal. Therefore, disregarding the irrationality of decision-makers may lead to misjudgments.

Although FMEA has many shortcomings, which were mentioned in this section and in the related literature frequently, this study focuses solely on shortcomings based on RPN calculation. The drawbacks of the RPN calculation stand on utility theory and assume that decision-makers are rational and the decision-making process is based on rationality. However, in real life, decision-makers may not be rational and while decision making under risk, irrationality, and uncertainty should be considered. The nature of prospect theory is appropriate to deal with the irrationality and uncertainty of the decision-making environment under risk. In the following section, concepts of uncertainty, irrationality, and prospect theory are explained in detail.

3. Uncertainty, Irrationality, and Prospect Theory

Decision-makers are expected to be rational during the decision-making process during RPN calculation in FMEA. However, risk factors including the likelihood of occurrence (O), severity (S) and difficulty of detection (D), which are used for RPN calculation, are uncertain factors and intuition and level of experience are required in order to overcome the uncertainty. Therefore, assuming the decision-making process rational can be seen as a failure.

To overcome this problem, risk attitudes are needed to be reflected during the decision-making process. They are in line with previous experiences and intuition of decision-makers during the decision-making process. By doing this, decision making under risk and uncertainty should be considered by covering irrationality. Moreover, to evaluate risks, a reference point is needed, and therefore, utility theory-based methods may overlook this. Reference point or, in other words, reference dependence, refers to the condition where outcomes are not certainly assessed but are related to some benchmark such as one's current wealth (Johnson & Busemeyer, 2010). To overcome these weaknesses, prospect theory is recommended in this study.

risks to the green supply chain are unforeseen events that might affect the green or environmentally friendly material movement, and even disturb the proposed flow of green materials and products from their point of origin to the point of consumption in business

Prospect theory is based on descriptions of decision-making under uncertain risky conditions. Introduced by Kahneman and Tversky in 1979, it was awarded the Nobel Prize in Economics

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4 in 2002 (Barberis, 2013). The decision under risk can be seen as a choice between prospect
5 and gambles (Kahneman & Tversky, 1979).
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8 Prospect theory was developed as a critique of expected utility theory, based on assessing the
9 utility of gain by comparison of the utilities of two stages of wealth. Although found to be
10 simple, Utility theory lacks a moving part in terms of final states of wealth. Moreover, utility
11 theory is also criticized in terms of accepting entirely rational axioms (Chen & Lee, 2000).
12 In prospect theory, since the decision-making process under risk is considered, the marginal
13 effect of gain or loss shall not be equal. Hence, one of the main contributions of prospect
14 theory is introducing weights of decisions (Johnson & Busemeyer, 2010).
15 Moreover, the reference point is the missing variable, which is the earlier state relative to the
16 evaluation of gains and losses. The main difference between Bernoulli's utility theory and
17 prospect theory is that, in the former, to determine the utility, only state of the wealth needs
18 to be known, while in the latter, reference state needs to be known additionally to determine
19 utility. Hence, Prospect theory has greater complexity.
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24 The three main principles of prospect theory were explained by Kahneman (2012) as follows:
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- 26 • The adaptation level is the neutral reference point, which is related to the evaluation.
27 When the outcomes are better than the reference point, it is stated as gains otherwise,
28 losses.
29
- 30 • Both sensory dimensions and the evaluation of change of wealth is applied by the
31 diminishing sensitivity principle.
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- 33 • Loss aversion is the third principle that is referred to as the condition of losses that are
34 heavier than gains when directly compared or weighed against each other.
35

36 Diminishing sensitivity for both gains and losses are represented by a salient feature, i.e., it
37 is S-shaped, where curves are not symmetrical. The slope of the function differs at the
38 reference point, because the reaction to losses are greater in effect than a reaction to gains,
39 referred to as loss aversion.
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42 In problems where both loss and gain are likely, loss aversion causes highly risk-averse
43 choices. In problems where a sure loss is inevitable, and when compared to a larger loss that
44 has a low probability, diminishing sensitivity causes risk-seeking.
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47 **4. Integration of Prospect Theory with FMEA**

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49 According to the given shortcomings, the structure of FMEA includes gain and loss aspects;
50 therefore, each element of FMEA can be analyzed through prospect theory. In Table 1, the
51 main principles of prospect theory including reference point, diminishing sensitivity and loss
52 aversion are given with their relationship with risk factors in FMEA.
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[TABLE 1 NEAR HERE]

To start with, as mentioned before, the reference point is the missing variable in utility theory, and a contribution of prospect theory is the identification of the reference state, in other words, the earlier state relative to which gain and losses are evaluated. In prospect theory, it is assumed that outcomes can be gains and losses, or outcomes can be below or above the reference point (Chiu & Wu, 2009). For FMEA, determining the reference point for severity and occurrence could be essential in terms of defining how severe and how frequent the situation is.

The principle of diminishing sensitivity refers to the effect of a change diminishing with the distance to the reference point. In other words, individuals are highly likely to realize the differences between small amounts rather than higher amounts (Barberis, 2013). For instance, a subjective difference between \$100 and \$200 is higher than between \$900 and \$1000, even the actual difference is same. In FMEA, the level of severity is related to the principle of diminishing sensitivity. Severity is perceived as a loss, and marginal utility decreases as the unit severity increases.

According to the corresponding prospect theory dimensions, risk-averse choices are caused by loss aversion in mixed gambles, where both gain and loss are possible. For FMEA, a gain situation can be defined as the detection of the risk before the occurrence. On the other hand, the loss can be defined as not being able to detect the risk, and causing the occurrence with high severity.

However, when, a loss is inevitable, where a sure loss is compared to a larger loss is more likely, diminishing sensitivity causes risk-seeking. In FMEA, a sure loss situation happens when it is not possible to detect the problem, and the occurrence is inevitable, with high severity.

Figure 1 shows the related relationships.

[FIGURE 1 NEAR HERE]

As it can be seen in the figure, risk attitudes of decision-makers under uncertain and risky environment can be explained by features of prospect theory. The reference point has not shown in the figure since it is related to both risk-seeking and risk-averse behaviors. The first research question is answered by a theoretical contribution with its detailed explanation and the suitability of prospect theory is explained.

5. Methodology

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4 In view of the theoretical base mentioned in the first research question, the second research
5 question is about the approach that should be applied. As previously mentioned in Section
6 2.1, most of the studies used utility theory-based MCDM and integrated approaches. In this
7 respect, the TODIM method is used in this study. Although there are studies that integrated
8 TODIM method with FMEA (Jia et al., 2017; Zhu et al., 2019; Huang et al., 2019), these
9 studies used TODIM for the prioritization of the risk factors, however, did not consider the
10 details of prospect theory. On the other hand, in this study, the focus is on decision-makers'
11 risk attitudes by considering different aspects of prospect theory including loss aversion,
12 reference point and diminishing sensitivity, and integrate them with FMEA. Some of the
13 previous studies that combined different MCDM methods with FMEA are summarized in
14 Table 2.

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20 [TABLE 2 NEAR HERE]

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22 Furthermore, in the literature, experts expressed the risk factors in fuzzy linguistic terms
23 using a fuzzy approach integrated into FMEA studies (Ghoushchi et al., 2019; Arabsheybani
24 et al., 2018). The fuzzy approach is used due to the vagueness present in the evaluation of
25 the relative importance of the three factors: a failure's likelihood of occurrence (O), severity
26 (S) and difficulty of detection (D), and the evaluation of potential failure modes according to
27 each criterion. Liu, Liu, and Liu (2013) summarized four advantages of using fuzzy logic in
28 FMEA methodology as follows:

- 29 1) As well as quantitative data; ambiguous, qualitative or imprecise information might
30 be utilized in risk assessment in a consistent manner.
- 31 2) It gives the opportunity to identify the association between severity, occurrence, and
32 detectability in a more flexible and realistic way.
- 33 3) It allows customization based on the nature of a process or a product in failure risk
34 evaluation function.
- 35 4) The fuzzy system can incorporate engineers' knowledge and expertise in FMEA
36 analysis. Additionally, Bowles and Pelaez (1995) emphasized two main advantages
37 of fuzzy approach in comparison to traditional FMEA: (i) both qualitative and
38 quantitative data can be employed; (ii) likelihood of occurrence, severity, and
39 difficulty of detection can be synthesized more flexibly (Braglia & Bevilacqua, 2000).

40
41 From this point of view, the aim of the proposed methodology is to present a new approach
42 to RPN calculation. The fuzzy logic is incorporated in the methodology, as its similar
43 applications are given in the literature. The reason to use fuzzy set theory is its capability to
44 deal with the uncertainties in the decision-making process. The advantage of using fuzzy
45 AHP is its capability to weigh the relevant set of criteria. The reason to hire TODIM is its
46 capability to prioritize the various alternatives in risky environment.

Figure 2 shows the research flowchart.

[FIGURE 2 NEAR HERE]

In the next sub-section, the fuzzy AHP and TODIM method are explained respectively.

5.1. Fuzzy Sets Theory

Due to subjective manners, the decision-makers deal with uncertainties in the decision-making process. Fuzzy set theory was introduced by Zadeh (1965) in order to reveal the usage of linguistic terms to overcome the subjectivity and vagueness of human judgment. A class of objects with a continuum of membership grades is called a fuzzy set. A tilde “~” is placed above when a fuzzy set is represented (Zadeh, 1965).

There are various fuzzy membership functions. In this paper, triangular fuzzy numbers were used. A triangular fuzzy number is indicated as (l_{ij}, m_{ij}, r_{ij}) referring the smallest possible, the most likely, and the largest possible values, respectively.

5.2. Fuzzy Analytic Hierarchy Process

5.2.1. Analytic Hierarchy Process (AHP)

The Analytical Hierarchy Process, proposed by Saaty (1980), is one of the most popular MCDM techniques. It can handle the criteria easily, and can effectively deal with quantitative and qualitative data. Like ANP, AHP is comprised using pairwise comparisons in order to identify the connections and priorities between the criteria. Decision-makers are able to weigh the two criteria, based on their relative importance regarding another criterion, indicating their assessments using Saaty’s scale (Saaty, 1980). Saaty’s scale enables decision-makers to determine the relative weights by representing their judgments in linguistic terms as equally important (E), moderately more important (MM), strongly more important (SM), very strongly more important (VSM), and extremely more important (EM) (Chung, Lee, & Pearn, 2005). Linguistic terms are then converted into numerical values, 1, 3, 5, 7, 9, respectively. The intermediate values, 2, 4, 6, and 8 are used to reflect a compromise between the above values. The relative importance of criterion i to criterion j is indicated by a score of a_{ij} , i.e., $a_{ij}=w_i/w_j$. A reciprocal value is found by comparing inversely, that is, $a_{ij}=1/a_{ji}$, indicating that criterion j is more important than criterion i (Onut, Kara, & Isik, 2009).

5.2.2. Fuzzy AHP: Fuzzy Extension of AHP

A fuzzy extension of AHP methodology differs from Saaty’s (1980) approach because it incorporates the fuzzy set theory. In fuzzy AHP, triangular fuzzy numbers are used to constitute the pairwise comparison matrices. Fuzzy AHP conforms to the relationships

between criteria using super matrices to obtain the relative importance weights (Onut, Kara, & Isik, 2009).

The fuzzy AHP approach is comprised of two steps (Duran & Aguilo, 2008):

1. Building a hierarchy of criteria,
2. Constituting a fuzzy judgment matrix.

The fuzzy judgment vector is attained for each criterion using pairwise comparisons. Although Saaty's (1980) scale of 1–9 has advantages including simplicity and ease of use, decision-makers experience uncertainties because of the subjective manner in which they make judgments. Pairwise comparison matrices are constructed by using triangular fuzzy numbers (l, m, r) in which $l \leq m \leq r$. The parameters l, m , and r indicate the smallest possible value, the most likely value, and the most promising value, respectively. The fuzzy matrix is shown as follows (Onut, Kara, & Isik, 2009).

The fuzzy judgment matrix, \tilde{A} , is constructed with all fuzzy judgment vectors (Duran & Aguilo, 2008).

$$\tilde{A} = \begin{pmatrix} (a_{11}^l, a_{11}^m, a_{11}^r) & (a_{12}^l, a_{12}^m, a_{12}^r) & \dots & (a_{1n}^l, a_{1n}^m, a_{1n}^r) \\ (a_{21}^l, a_{21}^m, a_{21}^r) & (a_{22}^l, a_{22}^m, a_{22}^r) & \dots & (a_{2n}^l, a_{2n}^m, a_{2n}^r) \\ \square & \square & \square & \square \\ (a_{m1}^l, a_{m1}^m, a_{m1}^r) & (a_{m1}^l, a_{m1}^m, a_{m1}^r) & \dots & (a_{mn}^l, a_{mn}^m, a_{mn}^r) \end{pmatrix}$$

The a_{mn} reflects the pairwise comparison of criterion m (row) with criterion n (column).

Using the scale of equally important (E), moderately more important (MM), strongly more important (SM), very strongly more important (VSM), and extremely more important (EM), we have the comparison matrix, \tilde{A} , where a_{ij} elements represent the estimative of the w_i/w_j relation (Duran & Aguilo, 2008).

Next, the eigenvector and the eigenvalue are computed. The fuzzy eigenvector of matrix \tilde{A} can be calculated using the following formula (Duran & Aguilo, 2008):

$$V_i = \left(\prod_{j=1}^n \tilde{a}_{ij} \right)^{1/n} \quad (1)$$

Consequently, we now have:

$$V_1 = (\tilde{a}_{11}x\tilde{a}_{12}x\tilde{a}_{13}x\dots x\tilde{a}_{1n})^{1/n} \quad (2)$$

$$V_n = (\tilde{a}_{n1}x\tilde{a}_{n2}x\tilde{a}_{n3}x\dots x\tilde{a}_{nn})^{1/n} \quad (3)$$

Eigenvector V_i is composite of the n triangular numbers shown as

$$V = (V_1^l, V_1^m, V_1^r; V_2^l, V_2^m, V_2^r; \dots; V_n^l, V_n^m, V_n^r) \quad (4)$$

Likewise, the traditional AHP, the eigenvector is then normalized by the following formula (Duran and Aguilo, 2008):

$$T = (w_1 / \sum w_i, w_2 / \sum w_i, \dots, w_n / \sum w_i) \quad (5)$$

where T is the normalized eigenvector. The weights of the criteria are extracted from this normalized eigenvector.

The result of any AHP analysis is only valid if it is consistent. The consistency ratio is computed by the following formula:

$$CR = CI / RI \quad (6)$$

where RI is Random Consistency Index (RI) created by Saaty (1980), and CI is found by:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (7)$$

If the consistency ratio (CR) is less than 10%, then the result of the AHP analysis is consistent.

5.3. TODIM

As mentioned before, the TODIM method is a discrete multi-criteria method. Since the TODIM is based on prospect theory, it reflects the shape of its value function same as the gains/losses function of Cumulative Prospect Theory, where gains and losses are always recognized regarding a reference point (Pereira, Gomes, & Paredes, 2013).

For the judgments of values, the TODIM method also allows the opportunity in judgments of value to use a verbal scale using a criteria hierarchy, fuzzy value judgments and the interdependence relationships among the alternatives (Tseng, Lin, Tan, Chen, & Chen, 2014).

TODIM is a useful technique for behavioral decision-making because it can overcome the decision-makers' limited rationality during the decision making process. The main concept of the method is to determine the dominance degree of each alternative in relation to others, using prospect theory-based utility function (Qin, Liu, & Pedrycz, 2017).

TODIM method is appropriate for both quantitative and qualitative factors, since, the linguistic scales of the qualitative factors can be transformed into cardinal ones and both scales are normalized. To measure the relative measure of the dominance of one alternative over the other, pairwise comparison is used in TODIM. For calculation, all factors of both relative gain/loss values for these alternatives are summed. The result shows either gain, loss or zeros according to the performance of alternatives by considering every criterion (Gomes & Rangel, 2009).

Before moving to mathematical formulations of the TODIM method, a decision matrix that includes alternatives and criteria must be described. Normalization of the values in the matrix is done by the division of the value of one alternative by the sum of all the alternatives for each organization. In given matrix where A_1, A_2, \dots, A_m are m alternatives, C_1, C_2, \dots, C_n are n criteria, P_{ij} is the rating of the alternative A_i regarding criterion C_j , and $\omega = (\omega_1, \omega_2, \dots, \omega_n)$, T is the weight vector related with the set of criteria $C = \{C_1, C_2, \dots, C_n\}$, which fulfills the below conditions $\omega_j \in [0, 1]$ and $\sum_{j=1}^n \omega_j = 1$.

A mathematical explanation of the TODIM method is summarized from the works of Gomes, Rangel, and Maranhao (2009) and Qin, Liu, and Pedrycz (2017) as follows;

Step 1: Calculation of the relative weight ω_{jr} of the criterion C_j to the reference criterion C_r that is shown as below:

$$\omega_{jr} = \omega_j / \omega_r \quad (j = 1, 2, \dots, n) \quad (8)$$

where ω_j indicates the weight of the criterion C_j and $\omega_r = \max \{ \omega_j \}$

Step 2: Calculation of the dominance degree of each alternative A_i over each alternative A_k regarding criterion C_j by using Eq. 9.

$$\Phi_c(A_i, A_k) = \begin{cases} 0 & \text{if } P_{ij} - P_{kj} > 0 \\ 0 & \text{if } P_{ij} - P_{kj} = 0 \\ 0 & \text{if } P_{ij} - P_{kj} < 0 \end{cases} \quad (9)$$

In Equation 9, θ represents the attenuation factor of the losses. When the θ is changed, shapes of the prospect theory value function alters in the negative quadrant. The range of the values of this parameter is $\theta > 0$, if $0 < \theta < 1$, then the effect of loss will increase; if $\theta > 1$, then the effect of loss will reduce.

Step 3: Calculation of the overall dominance degree of each alternative A_i over A_k regarding to criterion C_j as shown below:

$$\delta(A_i, A_k) = \sum_{j=1}^n \Phi_j(A_i, A_k) \quad (10)$$

Step 4: Calculation of the global prospect value of the alternative A_i ($i=1, 2, \dots, m$) by using the following equation:

$$\xi_i = \frac{\sum_{k=1}^m \delta(A_i, A_k) - \min \sum_{k=1}^m \delta(A_i, A_k)}{\max \sum_{k=1}^m \delta(A_i, A_k) - \min \sum_{k=1}^m \delta(A_i, A_k)} \quad (11)$$

Step 5. Based on the global prospect values of the alternatives, the ranking should be done. An increase in the value represents the better alternative A_i .

In the following section, a case study is presented.

6. Case Study

The application was conducted in a manufacturing firm located in Izmir producing hot-dip galvanizing and steel products. The firm's hot-dip galvanizing production process includes the activities of degreasing, acid pickling, rinsing, fluxing, drying, and dipping. In this process, as in all manufacturing processes, there are some risks, and possibilities that the manufacturing equipment may cause failures. In this manufacturing process, the failure modes are:

- 1) Kettle Failure (FM1): due to the permanently high temperature 7/24, the kettle may become unusable. In addition, molten zinc may drip, potentially causing the breakdown of the furnace, and finally, the dipping process may be halted, causing the interruption of the entire galvanizing process.
- 2) Generator Failure (FM2): For electricity-powered furnaces, it is important to have back-up generators in case of electricity shutdowns. In such a situation, the molten zinc may solidify and deteriorate the kettle.
- 3) Furnace Failure (FM3): Similar to a generator failure, in this situation, the molten zinc may solidify and deteriorate the kettle.
- 4) Crane Failure (FM4): In crane breakdowns, several problems may arise: the fall of the product into the kettle full of molten zinc may cause splashes and loss of zinc, and possibly

an interruption in the galvanizing of the material, or even production itself due to the failure of this most essential material handling equipment.

5) Dryer Failure (FM5): dryers are used to prevent small ‘explosions’ in the dipping process, caused by sudden water vaporization. In the case of dryer failure, these explosions may cause harm to workers and loss of zinc.

6) Tank Failure (FM6): tanks are used in degreasing, acid pickling and rinsing processes. Due to wear, which is especially rapid in the acid pickling stage, the tanks may deteriorate over time and may cause the related process to stop.

7) Operator Failures (FM7): several types of operator failures may occur. In manual or semi-automated systems, the malfunction of the crane, poor dipping performance, poor performance when lifting the products onto the jigs, and inaccuracy in the locations of holes drilled into the product to allow the molten zinc to escape. These operator failures, often caused by fatigue or poor training and orientation, may cause problems in quality and efficiency.

Data were collected through pairwise comparisons. Experts from the firm participated in the survey; the general manager, the operations manager, the IT manager, the consultant, and a member of the executive board. These authorities have been considered as experts due to their experience.

The weights of the likelihood of occurrence, severity, and difficulty of detection are calculated using the Fuzzy AHP method. After the weights of the factors are determined, the prioritization of failure modes are found using Fuzzy TODIM, in which decision-makers use linguistic variables to evaluate the ratings of failure modes with respective factors of FMEA

The weights of the factors, are obtained by the fuzzy AHP method, where Likelihood of Occurrence (C1) was found as 0.22, Severity (C2) was found as 0.44, and Difficulty of Detection (C3) was found as 0.34.

Triangular fuzzy numbers, seen in Table 3, have been used to express the preferences of decision-makers for the fuzzy TODIM method.

[TABLE 3 NEAR HERE]

The decision-makers’ preferences for failure modes with respect to each criterion are calculated. After the defuzzification process, the overall dominance degree of each alternative is received.

The global prospect values of alternatives can be seen in Table 4.

[TABLE 4 NEAR HERE]

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4 According to the result, the most crucial failure mode for the firm's attention is furnace
5 failure followed by generator failure, crane failure, tank failure, kettle failure, dryer failure,
6 and operator failure, respectively.
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9 **7. Implications**

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11 In this study, furnace and generator failure came out to be the top two leading risks. Both the
12 furnace failure and the generator failure may cause the molten zinc to solidify due to loss of
13 heating, causing a huge loss to the firm because it not possible to heat the solid zinc again to
14 melt. In such a situation, due to state transition, from liquid to solid, the expansion may occur,
15 and the solid zinc cannot be separated from the kettle. As a result, in addition to the loss of
16 zinc, kettle loss occurs due to the deformation of the kettle, which cannot be used anymore.
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20 In order to verify the results, an in-depth interview is conducted with the same experts, who
21 were involved in FMEA, in order to figure out whether the results are in accordance with
22 prospect theory or not.
23
24

25 An in-depth interview with the following open-ended questions was conducted:
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27

- 28 • What is the main task of managers?
- 29 • What would be the main reasons of production failure in a galvanizing plant?
- 30 • In terms of negative impact on the company in general, is there any difference
31 between a failure, that causes a production stoppage, lasting for one day, two days or
32 a week?
- 33 • Which one is more meaningful for you? The increase in productivity rate from 70%
34 to 90%, or 80% to 100%?
- 35 • Which one is more important for you? The continuation of production or productivity
36 increase.
- 37 • Could you compare the consequences of the production stoppage and the productivity
38 decrease?
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43
44 The managers stated that to keep production ongoing shall be the norm and the main task of
45 managers. They mentioned that furnace and generator failure can be defined as the nightmare
46 for galvanizers or the worst scenario that a galvanizing factory may encounter since the
47 consequences have low occurrence but high severity in which production may not continue
48 and stops for an indefinite time.
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51 They mentioned that after an initial increase in productivity in terms of gain, the positive
52 impact of productivity increase presents a diminishing feeling of achievement to the
53 managers. In terms of loss, they stated that the stoppage or failure in production has a great
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4 negative impact on the company for the first three days, but after that, the next four days, the
5 negative impact keeps a constant level, and it diminishes after one week.
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8 In addition to that, they declared that the task of preventing a production stoppage has a
9 higher priority in their agenda compared to an increase in productivity; therefore, the
10 situation proceeds managers to be risk-averse. They explained that the consequences due to
11 production failure are both external and internal, and bring penalties such as loss of customer
12 and goodwill, which are difficult to repair in the short term. Whereas a gain, in terms of
13 productivity, has internal consequences and may even be postponed.
14
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16
17 As mentioned before, the continuation of production is a reference point in the mindsets of
18 managers. The managers are willing to take all necessary precautions, remedies, and actions
19 in order to prevent any kind of production stoppages. Hence, FMEA has the capability to
20 support managers by considering the severity, detectability, and probability of various kinds
21 of production interruptions. In addition to that, FMEA can also support managers to conduct
22 scenario analysis. Thus, FMEA may play a crucial role to keep production continue and to
23 deal with potential causes of production stoppages and interruptions towards production in a
24 preventive manner.
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28 On the other hand, just similar to the reference point explanation given above, the stoppage
29 or failure of production is considered as a loss by managers, and its consequences cause
30 managers to react as loss-averse. This is due to the fact that the production stoppages are
31 considered as loss, and therefore given higher priority when compared to the productivity
32 increase, in terms of gains. Thus, preventive approaches that are concentrating on eliminating
33 or at least minimizing the consequences of production interventions and stoppages, are more
34 likely to be accepted and implemented by the managers.
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39 When the results are compared with the in-depth interview; it is observed that the results are
40 very much in line with prospect theory.
41

- 42 • The managers emphasized the continuation of the production, which can be translated
43 as the reference point in the minds of the managers.
- 44 • They mentioned that an increase in productivity, in terms of gain, and the stoppage
45 or failure in production, in terms of loss, have diminishing values.
- 46 • The risk-averse attitudes of managers are explained by the loss aversion, because loss,
47 in terms of failure or stoppage of production, is more critical than a gain, in terms of
48 productivity increase, due to higher weights that they assign for losses compared to
49 gains.
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The production managers can use FMEA as a preventative tool to deal with production stoppages. The method can be further improved and converted to a digital level that it can operate with streaming and real data. This can improve the responsiveness of the company.

In addition to production stoppages, the FMEA can contribute to the productivity and efficiency management of the company. The dimensions of FMEA can be analyzed to prevent causes of inefficiency and to improve the current system by enabling managers to take remedies and precautions against factors causing inefficiency.

Meanwhile, FMEA is not only capable to deal with the problems within production processes but also problems related to the product. Hence, FMEA shall be used as a tool starting from the design phase. Therefore, from a managerial point of view, FMEA should be implemented both as process FMEA and product FMEA by linking the design phase till production.

8. Conclusion

FMEA is a useful technique to identify and eliminate expected or potential failures, but some shortcomings are identified in the literature. This study focuses on shortcomings, which are caused by RPN calculations. To start with, different combinations of O, S, and D may produce exactly the same value of RPN; however, their hidden risk implications may be totally different. This situation may cause a waste of resources and time or a hidden high risky event may go unnoticed. Another weakness is the mathematical form adopted for calculating the RPN, which is strongly sensitive to variations in risk factor evaluations. Moreover, the relative importance among O, S, and D are not taken into consideration. Therefore, for weighting the aspects, the fuzzy AHP method is recommended in this study to eliminate the shortcomings. Since risk factors, including severity, occurrence and detection, are difficult to evaluate precisely; fuzzy logic is used as a solution method.

Moreover, RPN calculations are mainly based on utility theory, which considers the effect of a marginal change in gain or loss to be equal; however, in the decision-making process under risk, this marginal effect shall not be equal, as stated in prospect theory. Therefore, in this study, the applicability of prospect theory is tested using the fuzzy TODIM method, which is a prospect theory-based MCDM method.

According to the results of the study, furnace failure was found as the most important risk, which firms should pay the biggest attention to. Moreover, the generator failure is the second, crane failure is the third, tank failure is the fourth, kettle failure is the fifth, dryer failure is the sixth, and the operator failure is the last important failures.

In order to verify the results of the study, an in-depth interview was conducted with the participation of experts, and it is realized that the results are very much in line with Prospect

Theory. Therefore, practitioners may apply the proposed method to FMEA. The main limitation in this study was to propose theoretical and methodological solution for only four of the shortcomings of FMEA stated in the literature. Another limitation is that the proposed method is applied in one industry. Also, as with all MCDM applications, the research includes subjective judgments. The proposed model is generic and it can take the vagueness and ambiguities into consideration, but the results are not generalizable.

Future research may concentrate on other shortcomings of FMEA. On the other hand, different MCDM methods can be applied, e.g., gray theory can be used instead of fuzzy logic. In addition, the proposed method can be applied in various different industries as well as in different countries. Also, comparative analysis can be conducted among different companies, sectors and even countries.

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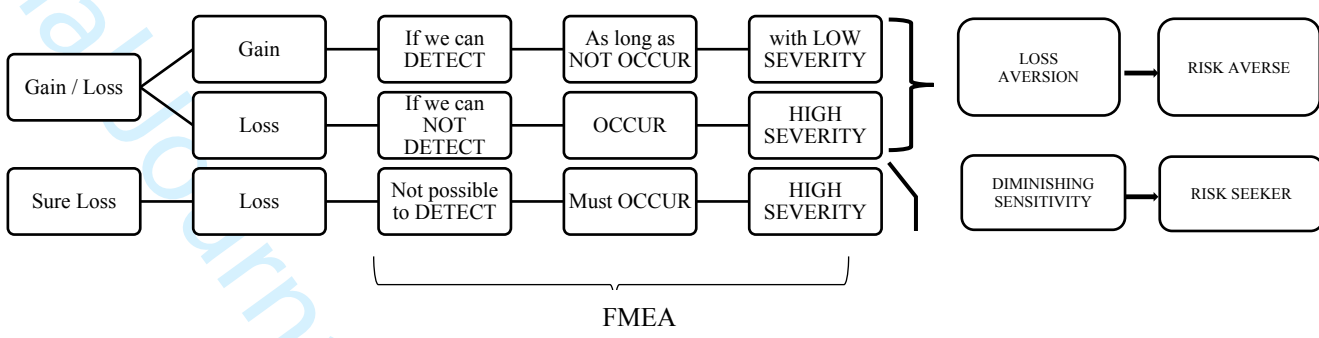


Figure 1: Integration of FMEA in to Risk Attitudes

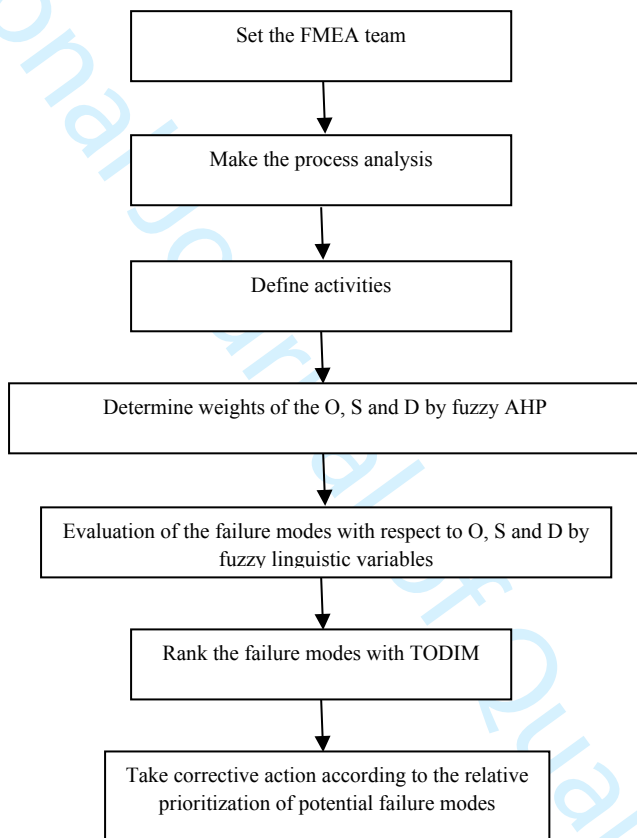


Figure 2: The research flowchart

Table 1: Relationship between Main Principles of Prospect Theory and Risk Factors

	Severity	Occurrence	Detectability
Reference Point	✓	✓	
Diminishing Sensitivity	✓	✓	✓
Loss Aversion	✓	✓	✓

Table 2: Previous Studies combining MCDM and FMEA

Author(s)	Method(s)	Aim of the Study
Hu et al. (2009)	Fuzzy AHP	Proposing an assessment framework to identify high risk green components.
Maheswaran and Loganathan (2013)	AHP and PROMETHEE	Eliminating the limitations present in the RPN based prioritization by integrating with MCDM.
Liu et al. (2015)	Fuzzy DEMATEL	Proposing a new integrated approach for FMEA based on fuzzy weighted average (FWA) and fuzzy DEMATEL .
Liu et al. (2015)	VIKOR, DEMATEL, and AHP	developing a new FMEA framework for evaluation, prioritization and improvement of failure modes.
Vahdani et al. (2015)	TOPSIS	proposing a new FMEA model combining technique for order of preference by TOPSIS and belief structure to overcome the shortcomings of the traditional index of FMEA.
Wang et al. (2016)	COPRAS and ANP	Proposing a new FMEA to assess and rank the risk of failure modes under interval-valued intuitionistic fuzzy context.
Jia et al. (2017)	TODIM	Applying linguistic distribution assessments to represent FMEA team members' risk evaluation information.
Arabsheybani et al. (2018)	Fuzzy MOORA	Evaluating suppliers and risk of suppliers in a sustainable supplier selection problem.
Fattahi and Khalilzadeh (2018)	Fuzzy MOORA and Fuzzy AHP	Proposing a novel fuzzy hybrid model for FMEA.
Liu et al. (2018)	TOPSIS	Proposing a novel integrated FMEA model based on cloud model theory and hierarchical technique for order of preference by TOPSIS to assess and rank the risk of failure modes.
Lo and Liou (2018)	Best-Worst Method and Grey Relational Analysis	Proposing a novel hybrid model for FMEA.
Huang et al. (2019)	TODIM	Proposing a new FMEA model and prioritize the risk of failure modes by integrating probabilistic linguistic term sets.
Mete (2019)	AHP and MOORA	Proposing FMEA-based AHP-MOORA integrated approach under Pythagorean fuzzy sets for assessing occupational risks

		in a natural gas pipeline construction project.
Ghoushchi et al. (2019)	MOORA and Fuzzy Best-Worst Method	Providing a new score to cover some of the shortcomings of traditional RPN score.
Zhu et al. (2019)	TODIM	Presenting a comprehensive FMEA model that could efficiently handle the preference interdependence.

Table 3: Linguistic Scale for fuzzy TODIM

Linguistic Terms	Triangular Fuzzy Numbers		
VG	0.75	1	1
G	0.50	0.75	1
M	0.25	0.50	0.75
B	0	0.25	0.50
VB	0	0	0.25

Table 4: Global Prospect Values of Alternatives

Global Values	
Furnace Failure (FM3)	1
Generator Failure (FM2)	0.767751
Crane Failure (FM4)	0.603689
Tank Failure (FM6)	0.534777
Kettle Failure (FM1)	0.470359
Dryer Failure (FM5)	0.08739
Operator Failures (FM7)	0