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# A compromise-based MADM approach for prioritizing failures: Integrating the RADAR method within the FMEA framework

**Nikola Komatina**[*]
Faculty of Engineering, University of Kragujevac, Kragujevac 34000, Republic of Serbia

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*Corresponding Author

Nikola Komatina
E-mail: nkomatina@kg.ac.rs

**ABSTRACT**

Multi-Attribute Decision-Making (MADM) methods are essential in decision-making processes, particularly in solving problems related to ranking and classifying alternatives. Among the MADM methods frequently utilized in the literature for ranking alternatives are distance-based or compromise-based methods. These methods have been widely applied for decades, with ongoing development leading to new approaches. One such approach is RAnking, based on the Distances And Range (RADAR) method. This novel distance-based method evaluates alternatives by considering their distance relative to the best and worst alternative values for a given criterion and the range between them. This paper applies the RADAR method to rank failure modes identified through a standard Failure Modes and Effects Analysis (FMEA) in an automotive industry company that produces rubber and plastic products. The results obtained from the RADAR method are compared with those derived from the traditional Risk Priority Number (RPN) approach. The comparison demonstrates that the RADAR method provides more distinct rankings, reducing the occurrence of ties between alternatives and thus offering a more nuanced and reliable decision-making tool in the context of failure mode prioritization.



## 1. INTRODUCTION

In the current industrial environment and practice, decision-making has become more complex. Traditional methods often struggle to address the intricacies of real-world challenges, especially in engineering, where reliability and accuracy are critical. As companies seek to enhance their performance and mitigate risks, there is a growing need to incorporate Multi-Attribute Decision-Making (MADM) methods into established frameworks like Failure Mode and Effects Analysis (FMEA). This paper presents RAnking based on Distances And Range (RADAR), a new approach that aims to tackle these issues by prioritizing stability across multiple criteria, thus providing practitioners with a more effective tool for making informed decisions in complex scenarios.

The primary goal of this paper is to introduce and validate RADAR, a new distance-based Multi-Attribute Decision-Making (MADM) method designed to tackle specific shortcomings found in traditional approaches. By emphasizing the significance of stability across multiple criteria, RADAR presents a solution that aligns closely with FMEA logic, potentially enhancing decision-making processes in engineering contexts.

This research is motivated by the need for more precise and reliable decision-making frameworks that can easily integrate with established methodologies, such as FMEA. As decision-making scenarios grow increasingly complex across various industries, this study aims to offer a method that complements and enhances traditional FMEA applications.

What sets this research apart is its introduction of RADAR as a MADM approach that prioritizes alternatives with stable performance across criteria rather than those that simply excel in one or two areas. This focus is especially important in industries where consistent reliability is essential, making a noteworthy contribution to the field of decision-making methodologies. By addressing these key points, this paper seeks to bridge a gap in the current literature and provide a practical tool for professionals in the field.

The following sections of this chapter provide a brief overview of the fundamentals of MADM methods, particularly the group of distance-based methods. Additionally, this chapter includes a literature review on integrating FMEA with existing MADM approaches.

Chapter 2 presents the related work. Chapter 3 gives the fundamentals of the RADAR method. This chapter describes the procedure of applying the method through the main steps and gives basic explanations. Also, this chapter gives two simple examples of the application of the method. Chapter 4 provides an illustrated step-by-step example of applying the RADAR method to a real-world case study. This chapter employs the method to rank failure modes identified in a standard FMEA analysis, demonstrating its practical application and effectiveness compared to traditional approaches like the Risk Priority Number (RPN). In Chapter 4, a sensitivity analysis of the obtained results was performed. The conclusion is given in chapter 5.

## 2. RELATED WORK

### 2.1. Multi-attribute decision-making

The Decision-Making problem is one of the most important problems in modern management practice. In order to make the decision-making process as precise as possible for decision-makers, i.e., managers, both at the operational and strategic levels, numerous methods have been developed. The group of methods that has stood out in recent decades for their development and application is the so-called Multicriteria Decision-Making (MCDM) methods. In the name of this group of methods, in addition to the term "Decision-Making," the terms "Optimization" and "Analysis" are also often used.

This paper discusses a special group of MCDM methods, namely MADM methods. MADM methods are special MCDM methods used to solve discrete optimization problems. In contrast to MADM methods, there is another type of MCDM method, namely Multi-Objective Decision Making (MODM) methods, which are used to solve continuous optimization problems. The main difference between MADM and MODM methods is that by applying the MADM method, the best available solutions are sought from the set of available solutions. In contrast, the MODM method seeks a solution based on objective function(s) and constraints by searching in continuous space [1].

MADM methods are used to solve various optimization problems. Some of them are used to classify alternatives (available solutions), others to determine the rank of alternatives, while some are used to determine the relative importance, i.e., the weight of the criteria. In addition, methods are used to determine the best or worst alternative [2], [3].

Modern scientific researches are very often based on the application of some of the MADM methods. The nature of these methods is such that they can be applied in any scientific discipline and can be a useful tool, which supports decision-making. In fact, the increasing prevalence of the application of MADM methods in the scientific literature speaks of how important they have become for solving not only scientific problems, but also problems in modern management practice.

Many authors have analyzed the application of MADM methods and reviewed the literature in this domain. Some papers reviewed the application of MCDM methods, some considered only MADM methods, while some authors considered the integration of MCDM/MADM methods with different types of fuzzy numbers and other similar concepts. In addition, some of the authors reviewed papers from a specific field in which MCDM/MADM methods were applied. Based on relevant research conducted by the authors [1], [4], [5], [6], it could be concluded that some methods are more common in the literature than others. MADM methods are used in various fields of science, starting from engineering [5], [7], management disciplines [8], [9] to economy [10], and certain natural sciences [11]. From the above literature, it can be seen that MCDM/MADM methods are adaptable and applicable to problems of different types. Therefore, this scientific discipline continues to develop, primarily through improving existing and new, improved, more precise, and more straightforward methods.

### 2.2. Distance-based MADM methods

In the relevant literature, MADM methods are usually divided into three groups [12], [13], [14], [15]:

a. Utility-based methods,
b. Outranking methods and
c. Distance-based or compromise-based methods.

In this paper, the special focus is on distance-based methods. The best-known and most widely used methods from this group are Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [16], VIKOR (in Serbian: VIšekriterijumska optimizacija i KOmpromisno Rešenje) [17], COmplex PRoportional ASsessment (COPRAS) [18] and Additive Ratio ASsessment (ARAS) [19]. However, common to these methods, which is why they are called distance-based methods, is that the solution to the ranking problem is based on the distance of the alternative from some smallest and largest (minimum and maximum) value.


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## 2.3. Fundamentals of failure mode and effects analysis

FMEA is a crucial method used to identify and evaluate potential failure modes within a system, aiming to enhance product or process reliability and safety. Originating from military procedures in 1949, FMEA has evolved significantly. Initially developed for military applications, it was adapted for various industries, including automotive, aerospace, and healthcare [20], [21]. FMEA involves assessing potential failure modes, their causes, and their effects on the system. The Risk Priority Number (RPN) is central to this process, calculated by multiplying three Risk factors: Severity (S), Occurrence (O), and Detection (D): $RPN = S \cdot O \cdot D$.

Where RPN values range from 1 to 1000 [20], [22], [23], the method helps prioritize failure modes based on their RPN, with higher values indicating more critical issues.

In practice, the interpretation of RPN thresholds varies. In the automotive industry, failure modes with high RPN values, or where any parameter (S, O, or D) is high, are typically considered critical [24]. Schuller *et al*. [25] suggest focusing on failure modes with parameters rated 9 or 10. Conversely, depending on their specific needs, different sectors may use varied scales for RPN values [26].

FMEA analysis is conducted by a dedicated team known as the FMEA team. This team should include members knowledgeable in both FMEA methodology and the relevant business processes, such as design or manufacturing. A multidisciplinary team is preferred, often comprising experts from production, quality, maintenance, technology, and design. Decisions are generally made by consensus [27].

In summary, FMEA is a widely used technique for risk assessment, with its application spanning various industries and evolving to address different sector-specific needs. Its core elements, including the calculation of RPN and the formation of a multidisciplinary team, are essential for effective risk management. Notably, in the automotive industry, the use of FMEA is mandatory, as specified by international standards, underscoring its critical role in ensuring product quality and safety.

## 2.4. Extension of FMEA through the application of MADM methods

The combination of FMEA analysis with various MADM approaches is common and current in the relevant literature. There are many studies where FMEA analysis is combined with different fuzzy MADM approaches. Since this paper focuses on developing a new MADM method and its application to a real engineering problem, fuzzy set theory and related disciplines have not been considered. Therefore, the literature review analyzed studies in which FMEA was combined with MADM methods using crisp values.

In the last five years, several studies have been published where the authors attempted to overcome the limitations of FMEA analysis by using MADM methods. Table 1 presents the domain of application, the method used, and the approach for determining the criteria weights.

As shown in Table 1, the authors most commonly used TOPSIS [16] and VIKOR [17] methods to determine the ranking (priority) of failures. Regarding the determination of criteria weights, the Shannon entropy method [28], [29], [30] was most frequently used, while some authors applied MADM methods [31], [32]. In the study by Hettiarachchi *et al.* [33], the authors determined the criteria weights through direct assessment.

**Table 1.** Application of FMEA in Combination with MADM Methods

| Domain of application | Method | Criteria weighting approach | Reference |
|---|---|---|---|
| Machine tool manufacturing | SAW, VIKOR, GRA, COPRAS | DEMATEL | Lo, *et al.* [31] |
| Dumpers in open-cast mining | TOPSIS | Shannon entropy method | Pradeep Kumar *et al.* [28] |
| Gas company | VIKOR | SWARA | Hamta *et al.* [32] |
| Oil wells drilling | TOPSIS | Shannon entropy method | Afzali Behbahani *et al.* [29] |
| Dairy and ice cream production | TOPSIS | Shannon entropy method | Sharifi *et al.* [30] |
| Service industry | VIKOR | Direct assessment | Hettiarachchi *et al.* [33] |
| Automotive industry | RADAR | Literature (AHP and BWM) | / |

In this paper, the new RADAR method was applied alongside the TOPSIS method, the most commonly used in the literature, and the ARAS method, which also belongs to the group of compromise methods. Comparison with the VIKOR method was not considered appropriate, as the results obtained can deviate depending on the decision-making coefficient, making it unreliable for comparison.

The criteria weights in this study were determined based on data from the literature. Specifically, research conducted in multiple automotive industry companies, including the company where the case study in this paper was carried out, served as the basis for determining the weighting coefficients. Therefore, this research partially builds upon the aforementioned studies. In the mentioned studies, the weights of the criteria were determined using the Analytic Hierarchy Process (AHP) [34] and the Best-Worst Method (BWM) [35].

## 3. RESEARCH METHODS

### 3.1. Basic explanations

The RADAR method is a new MADM approach, where the ranking of alternatives is based on their distance from the smallest and most significant value of an alternative within the considered criterion and the range between the largest and smallest value of alternatives for the considered criterion.

The proposed method has certain characteristics based on which its applicability to the (potential) considered problem can be determined. The basic characteristics of the RADAR method are:

(a) When ranking the alternatives, several aspects are taken into account:
   1. the value of the alternative for the considered criterion,
   2. criteria weights,
   3. permanence (stability) of the alternative according to all criteria and
   4. the high value of an alternative for a particular criterion.

(b) The method has a defined calculation check mechanism.

(c) The rank obtained using this method does not have too many deviations compared to other distance-based methods.

Ranking using the RADAR method is done, as with any other MADM method, based on the value of the alternatives and the relative importance of the criteria. However, the main characteristic of the RADAR method is that when the alternatives have (almost) equal total (aggregated) values, preference is given to the alternative with a "less bad" ranking according to one of some criteria. Only a second aspect of comparison is the situation in which an alternative has a high rank according to one of the criteria. These phenomena will be explained in section 3.3.

One of the mandatory steps in applying the RADAR method is checking the current calculating procedure. Also, it will be explained in section 2.3 in a simple example. In addition, by applying the RADAR method, the ranking of alternatives does not deviate too much from other distance-based MADM methods, i.e., it is almost identical. Comparative analysis will be presented in chapter 4.

To make the procedure of applying the RADAR method clearer to the readers, a short notation of the used terms and variables is given below:

$C$ – Total number of considered criteria.

$c, c = 1, \dots, C$ – Index of the considered criterion.

$A$ – Total number of considered alternatives.

$a, a = 1, \dots, A$ – Index of the considered alternative.

$[M_{ca}]_{C \times A}$ – Decision-making matrix. The value of each alternative according to each criterion.

$[\alpha_{ca}]_{C \times A}$ – Alpha ($\alpha$) matrix. It is based on the relation between the considered and best alternatives according to the considered criterion.

$[\beta_{ca}]_{C \times A}$ – Beta ($\beta$) matrix. It is based on the relation between the considered and worst alternatives according to the considered criterion.

$[E_{ca}]_{C \times A}$ – Empty range matrix. The range represents the difference between the distance of the considered alternative from the best and the distance from the worst alternative according to a certain criterion. It is expressed as an absolute value.

$[RR_{ca}]_{C \times A}$ – Relative relationship matrix. The relationship between the values for the considered alternative from the Alpha matrix and the sum of the values from the Beta matrix and the Empty range matrix. In this way, all three parameters are aggregated.

$W_c$ – The relative importance of the considered criterion.

$[WRR_{ca}]_{C \times A}$ – Weighted relative relationship matrix.

$RI_a$ – Aggregated ranking index. It is calculated based on the values from the Relative relationship matrix (when criteria have equal relative importance) or the Weighted relative relationship matrix at the level of each alternative. Based on this parameter, alternatives are ranked. The highest value of $RI_a$ means that the alternative is the first in the rank, while the lowest value of $RI_a$ means that the alternative is the last in the rank. For the alternative that is in first place in the ranking, the value of $RI_a$ is always 1.

### 3.2. Steps of RADAR method

The proposed method can be realized through the following steps, which are illustrated by the accompanying example in section 2.3:

***Step 1.*** Defining the set of criteria $c, c = 1, \dots, C$ and set of alternatives $a, a = 1, \dots, A$, and constructing the decision-making matrix:

$$[M_{ca}]_{C \times A}$$

Where $C$ is a total number of considered criteria, and $c, c = 1, \dots, C$ is an index of considered criteria. Also, $A$ is the total number of considered alternatives, and $a, a = 1, \dots, A$ is an index of considered alternative.

***Step 2.*** Construct the maximum proportion matrix, $\alpha$:

$$[\alpha_{ca}]_{C \times A}$$

For the benefit type of criteria:

$$\alpha_{ca} = \frac{\frac{\max_a M_{ca}}{M_{ca}}}{\left(\left(\frac{\max_a M_{ca}}{M_{ca}}\right) + \left(\frac{M_{ca}}{\min_a M_{ca}}\right)\right)} \quad (1)$$



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For the cost type of criteria:

$$\alpha_{ca} = \frac{\frac{M_{ca}}{\min_a M_{ca}}}{\left(\left(\frac{\max_a M_{ca}}{M_{ca}}\right)+\left(\frac{M_{ca}}{\min_a M_{ca}}\right)\right)} \quad (2)$$

***Step 3.*** Construct the minimum proportion matrix, $\beta$:

$$[\beta_{ca}]_{C\times A}$$

For the benefit type of criteria:

$$\beta_{ca} = \frac{\frac{M_{ca}}{\min_a M_{ca}}}{\left(\left(\frac{\max_a M_{ca}}{M_{ca}}\right)+\left(\frac{M_{ca}}{\min_a M_{ca}}\right)\right)} \quad (3)$$

For the cost type of criteria:

$$\beta_{ca} = \frac{\frac{\max_a M_{ca}}{M_{ca}}}{\left(\left(\frac{\max_a M_{ca}}{M_{ca}}\right)+\left(\frac{M_{ca}}{\min_a M_{ca}}\right)\right)} \quad (4)$$

***Step 4.*** Checking the width of the absolute range:

$$\alpha_{ca} + \beta_{ca} \approx 1 \quad (5)$$

In this way, the validity of the previous calculation procedure is tested.

***Step 5.*** Construct the empty range matrix:

$$[E_{ca}]_{C\times A}$$

where:

$$E_{ca} = |\alpha_{ca} - \beta_{ca}| \quad (6)$$

***Step 6.*** Construct the relative relationship matrix:

$$[RR_{ca}]_{C\times A}$$

where:

$$RR_{ca} = \frac{\alpha_{ca}}{\beta_{ca}+E_{ca}} \quad (7)$$

***Step 7.*** Construct the weighted relative relationship matrix:

$$[WRR_{ca}]_{C\times A}$$

where:

$$WRR_{ca} = RR_{ca} \cdot W_c \quad (8)$$

$W_c$ is the value of criteria relative importance (criteria weights).

This step is carried out if the considered criteria are not equally important.

***Step 8.*** Aggregated ranking index, $RI_a$ can be calculated for two cases:

a) When the considered criteria have an equal importance:

$$RI_a = \frac{\min \sum_{c=1}^{C} RR_a}{\sum_{c=1}^{C} RR_a} \quad (9)$$

b) When the considered criteria don't have an equal importance:

$$RI_a = \frac{\min \sum_{c=1}^{C} WRR_a}{\sum_{c=1}^{C} WRR_a} \quad (10)$$

***Step 9.*** Based on the calculated coefficient $RI_a$, the ranking of alternatives is determined. The first in the rank is the alternative that has the highest value of $RI_a$ (the value is always 1), while the last in the rank is the alternative that has the smallest value of $RI_a$.

### 3.3. A simple example of using the RADAR method

In this section, two simple examples of the application of the RADAR method are presented. The first example refers to the situation when all the criteria are of the benefit type. In the second example, benefit and cost-type criteria are considered. In these cases, the criteria are considered to be of equal relative importance.

***Example 1:***

Consider the problem of ranking 5 alternatives based on 3 criteria. All criteria are of benefit type, and they are equally important. The decision-making matrix is set according to Step 1 using a measurement scale [1-5] and can be presented in Table 2.

**Table 2.** Decision-making matrix

| | $c = 1$ | $c = 2$ | $c = 3$ |
|---|---|---|---|
| $a = 1$ | 2 | 4 | 1 |
| $a = 2$ | 2 | 1 | 4 |
| $a = 3$ | 4 | 5 | 3 |
| $a = 4$ | 4 | 4 | 1 |
| $a = 5$ | 1 | 3 | 2 |

Then, step 2 is applied, i.e., the matrix $\alpha$ is constructed. First, it is necessary to obtain $\max_a M_{ca}$, and $\min_a M_{ca}$:

$$\max_a M_{1a} = 4 \qquad \min_a M_{1a} = 1$$
$$\max_a M_{2a} = 5 \qquad \min_a M_{2a} = 1$$
$$\max_a M_{3a} = 4 \qquad \min_a M_{3a} = 1$$

The first element of the matrix $\alpha$ (Table 3), i.e. $\alpha_{11}$ is calculated as follows:

$$\alpha_{11} = \frac{\frac{\max_a M_{1a}}{M_{11}}}{\left(\left(\frac{\max_a M_{1a}}{M_{11}}\right)+\left(\frac{M_{11}}{\min_a M_{1a}}\right)\right)} = $$

$$= \frac{\frac{4}{2}}{\left(\left(\frac{4}{2}\right)+\left(\frac{2}{1}\right)\right)} = \frac{2}{4} = 0.5$$

**Table 3.** The maximum proportion matrix, $\alpha$

| | $c=1$ | $c=2$ | $c=3$ |
|---|---|---|---|
| $a=1$ | 0.5 | 0.238 | 0.8 |
| $a=2$ | 0.5 | 0.833 | 0.2 |
| $a=3$ | 0.2 | 0.167 | 0.308 |
| $a=4$ | 0.2 | 0.238 | 0.8 |
| $a=5$ | 0.8 | 0.357 | 0.5 |

Applying Step 3, the minimum proportion matrix, $\beta$, is constructed and presented in Table 4. The first element of this matrix is calculated as follows:

$$\beta_{11} = \frac{\frac{M_{11}}{\min_a M_{1a}}}{\left(\left(\frac{\max_a M_{1a}}{M_{11}}\right)+\left(\frac{M_{11}}{\min_a M_{1a}}\right)\right)} = \frac{\frac{2}{1}}{\left(\left(\frac{4}{2}\right)+\left(\frac{2}{1}\right)\right)} = \frac{2}{4} = 0.5$$

**Table 4.** The minimum proportion matrix, $\beta$

| | $c=1$ | $c=2$ | $c=3$ |
|---|---|---|---|
| $a=1$ | 0.5 | 0.762 | 0.2 |
| $a=2$ | 0.5 | 0.167 | 0.8 |
| $a=3$ | 0.8 | 0.833 | 0.692 |
| $a=4$ | 0.8 | 0.762 | 0.2 |
| $a=5$ | 0.2 | 0.643 | 0.5 |

The sum of the maximum proportion matrix elements and the minimum proportion matrix should equal approximately 1. In this way, the accuracy of the calculation is checked (Step 4). For example:

$$\alpha_{11} + \beta_{11} = 0.5 + 0.5 = 1$$

The empty range matrix is constructed using Step 5 (Table 5). The first element of this matrix is calculated as follows:

$$E_{11} = |\alpha_{11} - \beta_{11}| = |0.5 - 0.5| = 0$$

**Table 5.** The empty range matrix

| | $c=1$ | $c=2$ | $c=3$ |
|---|---|---|---|
| $a=1$ | 0 | 0.524 | 0.6 |
| $a=2$ | 0 | 0.667 | 0.6 |
| $a=3$ | 0.6 | 0.667 | 0.385 |
| $a=4$ | 0.6 | 0.524 | 0.6 |
| $a=5$ | 0.6 | 0.286 | 0 |

By applying step 6, the relative relationship matrix is constructed. This matrix is shown in Table 6, while the first element of the matrix is calculated as follows:

$$RR_{11} = \frac{\alpha_{11}}{\beta_{11} + E_{11}} = \frac{0.5}{0.5 + 0} = 1$$

**Table 6.** The relative relationship matrix

| | $c=1$ | $c=2$ | $c=3$ | $\sum_{c=1}^{3} RR_a$ |
|---|---|---|---|---|
| $a=1$ | 1 | 0.185 | 1 | 2.185 |
| $a=2$ | 1 | 1 | 0.143 | 2.143 |
| $a=3$ | 0.143 | 0.111 | 0.286 | 0.540 |
| $a=4$ | 0.143 | 0.185 | 1 | 1.328 |
| $a=5$ | 1 | 0.385 | 1 | 2.385 |
| | | | | $min = 0.540$ |

As the considered criteria have equal importance, Step 8 (Step 7 is skipped), i.e., aggregation of values, is approached as follows:

$$RI_1 = \frac{\min \sum_{c=1}^{3} RR_a}{\sum_{c=1}^{3} RR_1} = \frac{0.540}{1 + 0.185 + 1} = \frac{0.540}{2.185} \approx 0.247$$

$$RI_2 = 0.252$$

$$RI_3 = 1$$

$$RI_4 = 0.406$$

$$RI_5 = 0.226$$

Given that all criteria are of the same type, that for each criterion, the values are rated on a scale [1-5], and that the values are easily comparable, the obtained ranking (Step 9) can be described most easily by comparing it with the arithmetic mean determined for each alternative according to each criterion. This comparison is shown in Table 7.

**Table 7.** Comparison of the obtained rank with the rank obtained by applying the arithmetic mean

| | $RI_a$ | Rank | Arithmetic mean (decision-making matrix) | Rank |
|---|---|---|---|---|
| $a=1$ | 0.247 | 4 | 2.333 | 3-4 |
| $a=2$ | 0.252 | 3 | 2.333 | 3-4 |
| $a=3$ | 1 | 1 | 4 | 1 |
| $a=4$ | 0.406 | 2 | 3 | 2 |
| $a=5$ | 0.226 | 5 | 2 | 5 |

It can be seen in Table 7 an important feature of the RADAR method is that it takes into account the properties of the alternatives within the considered criterion. It can be seen in the table that the alternatives $a=1$ and $a=2$ occupy the same place in the ranking by a simple arithmetic mean. At first glance, it seems logical. However, the RADAR method considers that the alternative $a=2$ within the criterion $c=3$ represents the best-rated alternative. In this way, the alternative $a=2$ is given a certain advantage in relation to $a=1$, even though they essentially have


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equal marks.

***Example 2:***

Consider the problem of ranking 5 alternatives based on 3 criteria. Criteria $c = 1$ and $c = 2$ are of the benefit type, and criteria $c = 3$ is of the cost type. The decision-making matrix is set according to Step 1 by using a measurement scale [1-5], and can be presented in Table 8.

**Table 8.** Decision-making matrix

| | $c = 1$ | $c = 2$ | $c = 3$ |
|---|---|---|---|
| $a = 1$ | 3 | 4 | 1 |
| $a = 2$ | 2 | 1 | 4 |
| $a = 3$ | 4 | 5 | 3 |
| $a = 4$ | 4 | 4 | 1 |
| $a = 5$ | 1 | 3 | 2 |

For easier calculation procedure, Table 8 is almost the same as Table 2, except that $c = 3$ is of cost type, and there is a difference in the first element of the matrix. The calculation procedure is identical as in the first example, with the exception that for the criterion $c = 3$, expressions for the cost type of criterion are used. Therefore, the calculation procedure does not need to be shown in this example. Table 9 shows the relative relationship matrix (Step 6).

**Table 9.** The relative relationship matrix

| | $c = 1$ | $c = 2$ | $c = 3$ | $\sum_{c=1}^{3} RR_a$ |
|---|---|---|---|---|
| $a = 1$ | 0.286 | 0.185 | 0.143 | 0.614 |
| $a = 2$ | 1 | 1 | 1 | 3 |
| $a = 3$ | 0.143 | 0.111 | 1 | 1.254 |
| $a = 4$ | 0.143 | 0.185 | 0.143 | 0.471 |
| $a = 5$ | 1 | 0.385 | 1 | 2.385 |
| | | | | $min = 0.471$ |

$$RI_1 = \frac{\min \sum_{c=1}^{3} RR_a}{\sum_{c=1}^{3} RR_1} = \frac{0.471}{0.286 + 0.185 + 0.143} = \frac{0.471}{0.614} \approx 0.767$$

$$RI_2 = 0.157 \qquad RI_4 = 1$$

$$RI_3 = 0.376 \qquad RI_5 = 0.197$$

To easily interpret the obtained results, the values of the decision-making matrix for criterion $c = 3$ will be converted into a benefit criterion according to the formula $6 - M_{3a}$ and the arithmetic mean will be calculated. In other words, the value 5 becomes 1, 4 becomes 2, while 3 remains the same, and vice versa. The comparative rank matrix is shown in Table 10.

In Table 10, a situation occurs again where two alternatives, if the arithmetic mean is observed, have the same value: the same place in the ranking. By using the RADAR method, these two alternatives are not equal. Why is alternative $a = 1$ better than alternative $a = 3$? In this case, the value of the alternative $a = 1$ according to the criterion $c = 3$ is much higher (by 2) compared to $a = 3$. While for the other two criteria, $a = 1$ is slightly higher than $a = 3$ (by 1 each). As can be concluded, the RADAR method first considers alternatives that have smaller deviations, that is, that are not too "bad" according to one of the criteria. After that, it is considered according to how many criteria the alternative is ranked best. For this reason, $a = 1$ is better compared to the alternative $a = 3$. For all other alternatives, the ranking is obvious.

**Table 10.** Comparison of the obtained rank with the rank obtained by applying the arithmetic mean

| | $RI_a$ | Rank | Arithmetic mean (decision-making matrix) | Rank |
|---|---|---|---|---|
| $a = 1$ | 0.767 | 2 | 4 | 2-3 |
| $a = 2$ | 0.157 | 5 | 1.667 | 5 |
| $a = 3$ | 0.376 | 3 | 4 | 2-3 |
| $a = 4$ | 1 | 1 | 4.333 | 1 |
| $a = 5$ | 0.197 | 4 | 2.667 | 4 |

### 3.4. Basic features and rules of the RADAR method

The key features and rules of the RADAR method will be demonstrated in the following simple examples, i.e., decision-making matrices for evaluating 3 alternatives according to 3 criteria. In this way, different typical situations in ranking problems and the "behavior" of the method in each situation would be presented.

In the first case, the decision-making matrix is set so that the value of each alternative according to each criterion is 1. All criteria have equal relative importance and are of the same type.

$$\begin{bmatrix} & c = 1 & c = 2 & c = 3 \\ a = 1 & 1 & 1 & 1 \\ a = 2 & 1 & 1 & 1 \\ a = 3 & 1 & 1 & 1 \end{bmatrix} \Rightarrow \begin{matrix} RI_1 = 1 \\ RI_2 = 1 \\ RI_3 = 1 \end{matrix}$$

The second example shows a situation when alternatives have the same value according to the considered criterion, but the criteria are of different importance.

The following decision matrix shows the case when the criteria have different relative importance, as in the previous example, but the alternatives have values that are formed as follows: $M_{1a} = W_3$; $M_{2a} =$

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$W_2; M_{3a} = W_1; a, a = 1, \dots, 3.$

$$\begin{bmatrix} & W_1 = 0.5 & W_2 = 0.3 & W_3 = 0.2 \\ & c = 1 & c = 2 & c = 3 \\ a = 1 & 1 & 1 & 1 \\ a = 2 & 1 & 1 & 1 \\ a = 3 & 1 & 1 & 1 \end{bmatrix} \Rightarrow \begin{matrix} RI_1 = 1 \\ RI_2 = 1 \\ RI_3 = 1 \end{matrix}$$

$$\begin{bmatrix} & W_1 = 0.5 & W_2 = 0.3 & W_3 = 0.2 \\ & c = 1 & c = 2 & c = 3 \\ a = 1 & 0.2 & 0.3 & 0.5 \\ a = 2 & 0.2 & 0.3 & 0.5 \\ a = 3 & 0.2 & 0.3 & 0.5 \end{bmatrix} \Rightarrow \begin{matrix} RI_1 = 1 \\ RI_2 = 1 \\ RI_3 = 1 \end{matrix}$$

In the previous cases, examples where the alternatives have the same $RI_a$ were presented. In all the previously presented examples, all alternatives are expected to rank in the same place.

The following decision-making matrix shows a situation where the alternatives have the same overall values but differ depending on the criteria. As in the first case, the criteria have the same relative importance.

$$\begin{bmatrix} & c = 1 & c = 2 & c = 3 \\ a = 1 & 1 & 3 & 5 \\ a = 2 & 5 & 3 & 1 \\ a = 3 & 3 & 5 & 1 \end{bmatrix} \Rightarrow \begin{matrix} RI_1 = 0.859 \\ RI_2 = 0.859 \\ RI_3 = 1 \end{matrix}$$

In this case, a situation arises where the alternatives collectively have equal ratings, but their $RI_a$ differs. As can be seen in the attached decision-making matrix, $a = 3$ is better compared to the other two alternatives. Alternative $a = 1$ is worse compared to $a = 3$ because its value for criterion $c = 1$ is significantly lower compared to the other two alternatives. On the other hand, alternative $a = 2$ is worse than alternative $a = 3$ for the reason that alternative $a = 3$ has the smallest deviations in the ranking, looking at the criteria according to which it is not the best, more precisely for $c = 1$ it is in second place, and for $c = 3$ it is at the division of the second place.

In this way, the rule is confirmed that the RADAR method, when ranking, first takes into account the stability of the value/rank of the alternative according to all considered criteria. In this way, the overall assessment of options with a very poor value according to one (or more) of the criteria, and especially according to important criteria, is sufficiently reduced. Of course, for certain types of problems, this logic would not be appropriate. In such cases, decision-makers can resort to some other MADM approaches.

The next case refers to a situation where the alternatives have the same aggregate values, but the criteria have different weights. At the same time, the value relationship of the alternatives is such that no alternative achieves an advantage based on the previously stated rules. So, if all the criteria had the same relative importance, the coefficient $RI_a$ for all alternatives would be equal to 1. However, if the criteria have different weights, the following is obtained:

$$\begin{bmatrix} & W_1 = 0.5 & W_2 = 0.3 & W_3 = 0.2 \\ & c = 1 & c = 2 & c = 3 \\ a = 1 & 3 & 3 & 1 \\ a = 2 & 3 & 1 & 3 \\ a = 3 & 1 & 3 & 3 \end{bmatrix} \Rightarrow \begin{matrix} RI_1 = 1 \\ RI_2 = 0.818 \\ RI_3 = 0.6 \end{matrix}$$

From the shown example, it is very easy to conclude that the alternative $a = 1$, due to its values according to the two most important criteria, has the first place in the ranking. The second in the ranking is the alternative $a = 2$, which is expected, considering its values according to the most important criterion. Of course, the alternative $a = 3$ is the last in the ranking because it has the lowest value according to the most important criterion.

The examples presented in this section confirm some of the most important features and rules for applying the RADAR method. The aim of presenting these simple examples is to help decision-makers choose an adequate MADM method. As mentioned, the method should be selected according to the nature of the considered problem.

What can be pointed out as a constraint of the RADAR method is that the value 0 cannot be a member of the decision-making matrix. In that case, it would not be possible to carry out the calculation and not even the ranking. In other words, we would end up dividing a number by 0, which is certainly not possible. However, situations like this are not so prevalent in practice, so the mentioned shortcomings do not have to be so important.

## 4. RESULTS AND DISCUSSION

### 4.1. Case study: application of the radar method in FMEA

In this section, the ranking of the failure modes identified through the standard FMEA analysis has been performed. The FMEA report originates from an automotive industry company specializing in producing rubber and plastic products. The analyzed failure modes are presented in Table 11. In this case, the risk factors S, O, and D are considered criteria $c, c = 1, \dots, C$, while the failure modes are viewed as alternatives $a, a = 1, \dots, A$.


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**Table 11.** Identified Failure Modes (decision-making matrix)

| No. of Failure Mode | Failure Mode | Potential Effect | S | Potential Causes | O | Current Process Controls | D |
|---|---|---|---|---|---|---|---|
| $a = 1$ | Cutting length below the minimum length | Installation impossible, Complaint | 6 | Incorrectly set cutting device; Operator did not push the hose to the stop | 2 | Length control according to batch approval | 7 |
| $a = 2$ | Cutting length above maximum length | Difficult hose assembly, Higher risk of vehicle damage | 6 | Incorrectly set cutting device | 2 | Length control according to batch approval | 5 |
| $a = 3$ | Poorly attached fitting | Hose detachment from the fitting | 10 | Operator did not push the hose to the stop | 2 | Detected during pressure test operation | 4 |
| $a = 4$ | Over-tightened | Hose tearing | 10 | Improperly adjusted tightening | 2 | Pull-off force control according to batch approval | 5 |
| $a = 5$ | Under-tightened | Fitting detachment | 10 | Improperly adjusted tightening | 2 | Pull-off force control according to batch approval | 5 |
| $a = 6$ | No thread on the fitting | Installation impossible | 7 | Supplier error | 2 | Visual inspection | 7 |
| $a = 7$ | Insufficient thread length on the fitting | Brake system leakage | 7 | Supplier error | 3 | Incoming inspection | 10 |
| $a = 8$ | Misaligned tightening | Probe blockage, Reduced brake fluid flow | 9 | Improperly adjusted tightening | 2 | Tightening height control according to batch approval | 5 |
| $a = 9$ | Improperly placed sleeve | Difficult assembly | 5 | Spacer not used | 2 | Position control according to the guide | 5 |
| $a = 10$ | Inability to properly tighten | Aesthetic appearance | 2 | Operator error | 2 | Position control according to the guide | 5 |
| $a = 11$ | Incorrect position | Sleeve damage, Aesthetic appearance | 2 | Operator error | 2 | Position control according to the guide | 5 |
| $a = 12$ | Improper tightening shape | Sleeve damage, Aesthetic appearance | 2 | Operator error | 2 | Shape control according to the reference sample | 5 |
| $a = 13$ | Poorly attached fitting | Hose detachment from the fitting | 10 | Operator did not push the hose to the stop | 2 | Detected during pressure test operation | 4 |
| $a = 14$ | Over-tightened | Hose tearing | 10 | Improperly adjusted tightening | 2 | Pull-off force control according to batch approval | 5 |
| $a = 15$ | Under-tightened | Fitting detachment | 10 | Improperly adjusted tightening | 2 | Pull-off force control according to batch approval | 5 |
| $a = 16$ | No thread on the fitting | Installation impossible, Complaint | 6 | Supplier error | 2 | Visual inspection | 8 |
| $a = 17$ | Insufficient thread length on the fitting | Brake system leakage | 7 | Supplier error | 3 | Incoming inspection | 10 |
| $a = 18$ | Misaligned tightening | Probe blockage, Reduced brake fluid flow | 9 | Improperly adjusted tightening | 2 | Tightening height control according to batch approval | 5 |
| $a = 19$ | Incorrect angle between fittings | Difficult hose assembly, Higher risk of vehicle damage | 9 | Incorrectly positioned fitting | 2 | Position control according to batch approval, position control during tightening | 8 |
| $a = 20$ | Leakage, swelling, hose bursting | Scrap | 10 | Incorrectly positioned and tightened fitting | 2 | 100% inspection | 4 |
| $a = 21$ | Probe does not pass | Reduced brake fluid flow | 7 | Improperly adjusted tightening | 3 | 100% inspection | 4 |
| $a = 22$ | Incorrectly marked fitting | Complaint | 2 | Operator error | 3 | 100% visual inspection | 7 |
| $a = 23$ | Incorrect quantity | Complaint | 6 | Operator error | 2 | Quantity control | 2 |
| $a = 24$ | Label replacement | Complaint | 6 | Operator error, Incorrect label applied | 2 | Proper identification and labeling/professional training for workers | 2 |
| $a = 25$ | Mixing hoses from process with finished products | Installation impossible, Complaint | 6 | Untrained workers, Inadequate logistics during packing operation | 3 | Proper identification and labeling/professional training for workers | 8 |

In this case, it was considered that the risk factors S, O, and D have different importance, meaning that as criteria, they carry different weights. The weights were determined based on relevant literature. In Komatina *et al*. [36], the authors assigned the weights to the criteria as follows:

$$(W_1 = 0.69) \quad (W_2 = 0.19) \quad (W_3 = 0.11)$$

Additionally, in [37], the authors suggest that the weight of the criteria is:

$$(W_1 = 0.66) \quad (W_2 = 0.23) \quad (W_3 = 0.11)$$

By applying the arithmetic mean operator, these weights were aggregated, and the following values were adopted in this case:

$$(W_1 = 0.68) \quad (W_2 = 0.21) \quad (W_3 = 0.11)$$

Determination of the $\max_a M_{ca}$, and $\min_a M_{ca}$ values:

$$\max_a M_{1a} = 10 \qquad \min_a M_{1a} = 2$$
$$\max_a M_{2a} = 3 \qquad \min_a M_{2a} = 2$$
$$\max_a M_{3a} = 10 \qquad \min_a M_{3a} = 2$$

The first element of the matrix $\alpha$ (Table 12), i.e. $\alpha_{11}$ is calculated as follows:

$$\alpha_{11} = \frac{\frac{\max_a M_{1a}}{M_{11}}}{\left(\left(\frac{\max_a M_{1a}}{M_{11}}\right) + \left(\frac{M_{11}}{\min_a M_{1a}}\right)\right)} = \frac{\frac{10}{6}}{\left(\left(\frac{10}{6}\right) + \left(\frac{6}{2}\right)\right)} = 0.357$$

Applying Step 3, the minimum proportion matrix, $\beta$, is constructed and presented in Table 13. The first element of this matrix is calculated as follows:

$$\beta_{11} = \frac{\frac{M_{11}}{\min_a M_{1a}}}{\left(\left(\frac{\max_a M_{1a}}{M_{11}}\right) + \left(\frac{M_{11}}{\min_a M_{1a}}\right)\right)} = \frac{\frac{6}{2}}{\left(\left(\frac{10}{6}\right) + \left(\frac{6}{2}\right)\right)} = 0.643$$

**Table 12.** The maximum proportion matrix, $\alpha$

| | $c = 1$ | $c = 2$ | $c = 3$ | | $c = 1$ | $c = 2$ | $c = 3$ |
|---|---|---|---|---|---|---|---|
| $a = 1$ | 0.357 | 0.600 | 0.290 | $a = 14$ | 0.167 | 0.600 | 0.444 |
| $a = 2$ | 0.357 | 0.600 | 0.444 | $a = 15$ | 0.167 | 0.600 | 0.444 |
| $a = 3$ | 0.167 | 0.600 | 0.556 | $a = 16$ | 0.357 | 0.600 | 0.238 |
| $a = 4$ | 0.167 | 0.600 | 0.444 | $a = 17$ | 0.290 | 0.400 | 0.167 |
| $a = 5$ | 0.167 | 0.600 | 0.444 | $a = 18$ | 0.198 | 0.600 | 0.444 |
| $a = 6$ | 0.290 | 0.600 | 0.290 | $a = 19$ | 0.198 | 0.600 | 0.238 |
| $a = 7$ | 0.290 | 0.400 | 0.167 | $a = 20$ | 0.167 | 0.600 | 0.556 |
| $a = 8$ | 0.198 | 0.600 | 0.444 | $a = 21$ | 0.290 | 0.400 | 0.556 |
| $a = 9$ | 0.444 | 0.600 | 0.444 | $a = 22$ | 0.833 | 0.400 | 0.290 |
| $a = 10$ | 0.833 | 0.600 | 0.444 | $a = 23$ | 0.357 | 0.600 | 0.833 |
| $a = 11$ | 0.833 | 0.600 | 0.444 | $a = 24$ | 0.357 | 0.600 | 0.833 |
| $a = 12$ | 0.833 | 0.600 | 0.444 | $a = 25$ | 0.357 | 0.400 | 0.238 |
| $a = 13$ | 0.167 | 0.600 | 0.556 | | | | |

**Table 13.** The minimum proportion matrix, $\beta$

| | $c = 1$ | $c = 2$ | $c = 3$ | | $c = 1$ | $c = 2$ | $c = 3$ |
|---|---|---|---|---|---|---|---|
| $a = 1$ | 0.643 | 0.400 | 0.710 | $a = 14$ | 0.833 | 0.400 | 0.556 |
| $a = 2$ | 0.643 | 0.400 | 0.556 | $a = 15$ | 0.833 | 0.400 | 0.556 |
| $a = 3$ | 0.833 | 0.400 | 0.444 | $a = 16$ | 0.643 | 0.400 | 0.762 |
| $a = 4$ | 0.833 | 0.400 | 0.556 | $a = 17$ | 0.710 | 0.600 | 0.833 |
| $a = 5$ | 0.833 | 0.400 | 0.556 | $a = 18$ | 0.802 | 0.400 | 0.556 |
| $a = 6$ | 0.710 | 0.400 | 0.710 | $a = 19$ | 0.802 | 0.400 | 0.762 |
| $a = 7$ | 0.710 | 0.600 | 0.833 | $a = 20$ | 0.833 | 0.400 | 0.444 |
| $a = 8$ | 0.802 | 0.400 | 0.556 | $a = 21$ | 0.710 | 0.600 | 0.444 |
| $a = 9$ | 0.556 | 0.400 | 0.556 | $a = 22$ | 0.167 | 0.600 | 0.710 |
| $a = 10$ | 0.167 | 0.400 | 0.556 | $a = 23$ | 0.643 | 0.400 | 0.167 |
| $a = 11$ | 0.167 | 0.400 | 0.556 | $a = 24$ | 0.643 | 0.400 | 0.167 |
| $a = 12$ | 0.167 | 0.400 | 0.556 | $a = 25$ | 0.643 | 0.600 | 0.762 |
| $a = 13$ | 0.833 | 0.400 | 0.444 | | | | |

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The accuracy of the calculation is checked (Step 4):

$$\alpha_{11} + \beta_{11} = 0.357 + 0.643 = 1$$

Using Step 5, the empty range matrix is constructed (Table 14). The first element of this matrix is calculated as follows:

$$E_{11} = |\alpha_{11} - \beta_{11}| = |0.357 - 0.643| = 0.286$$

By applying step 6 and step 7, the weighted relative relationship matrix is shown in Table 15, while the first element of the matrix is calculated as follows:

$$WRR_{11} = \frac{\alpha_{11}}{\beta_{11} + E_{11}} \cdot W_1 = \frac{0.357}{0.643 + 0.286} \cdot 0.68 = 0.385 \cdot 0.68 = 0.262$$

Minimum value of $WRR_a$ coefficient is 0.292.

Step 8, i.e., aggregation of values $RI_a$ (Table 16), is approached as follows:

$$RI_1 = \frac{\min \sum_{c=1}^{3} WRR_a}{\sum_{c=1}^{3} WRR_1} = \frac{0.292}{0.500} \approx 0.584$$

Based on the results obtained using the RADAR method, it can be determined that failure modes $a = 7$ i $a = 17$ are ranked first, while failures $a = 23$, $a = 24$ i $a = 25$ occupy the last positions in the ranking. The results have been compared with the traditional RPN approach To illustrate the contribution of applying the RADAR method (Table 17).

Applying the RADAR method has demonstrated satisfactory and precise results, proving to be a stable tool for ranking. Although the RADAR method provides results largely similar to those obtained with the traditional RPN approach, it exhibits several key advantages. One of the most important is its ability to reduce the number of identical ranks among different failure modes. While the RPN approach often results in the same rank being assigned to multiple failure modes, which can complicate decision-making, the RADAR method assigns a unique rank to a greater number of failure modes (9 compared to only 5 with the RPN approach).

**Table 14.** The empty range matrix

| | $c = 1$ | $c = 2$ | $c = 3$ | | $c = 1$ | $c = 2$ | $c = 3$ |
|---|---|---|---|---|---|---|---|
| $a = 1$ | 0.286 | 0.200 | 0.420 | $a = 14$ | 0.667 | 0.200 | 0.111 |
| $a = 2$ | 0.286 | 0.200 | 0.111 | $a = 15$ | 0.667 | 0.200 | 0.111 |
| $a = 3$ | 0.667 | 0.200 | 0.111 | $a = 16$ | 0.286 | 0.200 | 0.524 |
| $a = 4$ | 0.667 | 0.200 | 0.111 | $a = 17$ | 0.420 | 0.200 | 0.667 |
| $a = 5$ | 0.667 | 0.200 | 0.111 | $a = 18$ | 0.604 | 0.200 | 0.111 |
| $a = 6$ | 0.420 | 0.200 | 0.420 | $a = 19$ | 0.604 | 0.200 | 0.524 |
| $a = 7$ | 0.420 | 0.200 | 0.667 | $a = 20$ | 0.667 | 0.200 | 0.111 |
| $a = 8$ | 0.604 | 0.200 | 0.111 | $a = 21$ | 0.420 | 0.200 | 0.111 |
| $a = 9$ | 0.111 | 0.200 | 0.111 | $a = 22$ | 0.667 | 0.200 | 0.420 |
| $a = 10$ | 0.667 | 0.200 | 0.111 | $a = 23$ | 0.286 | 0.200 | 0.667 |
| $a = 11$ | 0.667 | 0.200 | 0.111 | $a = 24$ | 0.286 | 0.200 | 0.667 |
| $a = 12$ | 0.667 | 0.200 | 0.111 | $a = 25$ | 0.286 | 0.200 | 0.524 |
| $a = 13$ | 0.667 | 0.200 | 0.111 | | | | |

**Table 15.** The relative relationship matrix

| | $c = 1$ | $c = 2$ | $c = 3$ | $\sum_{c=1}^{3} WRR_a$ | | $c = 1$ | $c = 2$ | $c = 3$ | $\sum_{c=1}^{3} WRR_a$ |
|---|---|---|---|---|---|---|---|---|---|
| $a = 1$ | 0.262 | 0.210 | 0.028 | 0.500 | $a = 14$ | 0.076 | 0.210 | 0.073 | 0.359 |
| $a = 2$ | 0.262 | 0.210 | 0.073 | 0.545 | $a = 15$ | 0.076 | 0.210 | 0.073 | 0.359 |
| $a = 3$ | 0.076 | 0.210 | 0.110 | 0.396 | $a = 16$ | 0.262 | 0.210 | 0.020 | 0.492 |
| $a = 4$ | 0.076 | 0.210 | 0.073 | 0.359 | $a = 17$ | 0.174 | 0.105 | 0.012 | 0.292 |
| $a = 5$ | 0.076 | 0.210 | 0.073 | 0.359 | $a = 18$ | 0.096 | 0.210 | 0.073 | 0.379 |
| $a = 6$ | 0.174 | 0.210 | 0.028 | 0.413 | $a = 19$ | 0.096 | 0.210 | 0.020 | 0.326 |
| $a = 7$ | 0.174 | 0.105 | 0.012 | 0.292 | $a = 20$ | 0.076 | 0.210 | 0.110 | 0.396 |
| $a = 8$ | 0.096 | 0.210 | 0.073 | 0.379 | $a = 21$ | 0.174 | 0.105 | 0.110 | 0.389 |
| $a = 9$ | 0.453 | 0.210 | 0.073 | 0.737 | $a = 22$ | 0.680 | 0.105 | 0.028 | 0.813 |
| $a = 10$ | 0.680 | 0.210 | 0.073 | 0.963 | $a = 23$ | 0.262 | 0.210 | 0.110 | 0.582 |
| $a = 11$ | 0.680 | 0.210 | 0.073 | 0.963 | $a = 24$ | 0.262 | 0.210 | 0.110 | 0.582 |
| $a = 12$ | 0.680 | 0.210 | 0.073 | 0.963 | $a = 25$ | 0.262 | 0.105 | 0.020 | 0.387 |
| $a = 13$ | 0.076 | 0.210 | 0.110 | 0.396 | | | | | |

**Table 16.** Aggregated ranking index, $RI_a$ and rank of failure modes

| | $RI_a$ | Rank | | $RI_a$ | Rank | | $RI_a$ | Rank | | $RI_a$ | Rank |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $a = 1$ | 0.584 | 17 | $a = 8$ | 0.770 | 8-9 | $a = 15$ | 0.814 | 4-7 | $a = 22$ | 0.359 | 22 |
| $a = 2$ | 0.536 | 18 | $a = 9$ | 0.396 | 21 | $a = 16$ | 0.594 | 16 | $a = 23$ | 0.502 | 19-20 |
| $a = 3$ | 0.738 | 12-14 | $a = 10$ | 0.303 | 23-25 | $a = 17$ | 1.000 | 1-2 | $a = 24$ | 0.502 | 19-20 |
| $a = 4$ | 0.814 | 4-7 | $a = 11$ | 0.303 | 23-25 | $a = 18$ | 0.770 | 8-9 | $a = 25$ | 0.755 | 10 |
| $a = 5$ | 0.814 | 4-7 | $a = 12$ | 0.303 | 23-25 | $a = 19$ | 0.895 | 3 | | | |
| $a = 6$ | 0.708 | 15 | $a = 13$ | 0.738 | 12-14 | $a = 20$ | 0.738 | 12-14 | | | |
| $a = 7$ | 1.000 | 1-2 | $a = 14$ | 0.814 | 4-7 | $a = 21$ | 0.750 | 11 | | | |

**Table 17.** Application of the RADAR method compared to the traditional RPN approach

| | RADAR | RPN | | RADAR | RPN | | RADAR | RPN | | RADAR | RPN |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $a = 1$ | 17 | 12-13 | $a = 8$ | 8-9 | 11-12 | $a = 15$ | 4-7 | 5-8 | $a = 22$ | 22 | 19 |
| $a = 2$ | 18 | 17 | $a = 9$ | 21 | 18 | $a = 16$ | 16 | 10 | $a = 23$ | 19-20 | 20-21 |
| $a = 3$ | 12-14 | 14-16 | $a = 10$ | 23-25 | 22-25 | $a = 17$ | 1-2 | 1-2 | $a = 24$ | 19-20 | 20-21 |
| $a = 4$ | 4-7 | 5-8 | $a = 11$ | 23-25 | 22-25 | $a = 18$ | 8-9 | 11-12 | $a = 25$ | 10 | 3-4 |
| $a = 5$ | 4-7 | 5-8 | $a = 12$ | 23-25 | 22-25 | $a = 19$ | 3 | 3-4 | | | |
| $a = 6$ | 15 | 9 | $a = 13$ | 12-14 | 14-16 | $a = 20$ | 12-14 | 14-16 | | | |
| $a = 7$ | 1-2 | 1-2 | $a = 14$ | 4-7 | 5-8 | $a = 21$ | 11 | 12-13 | | | |

This characteristic of the RADAR method allows for clearer differentiation between different failure modes, making it easier to prioritize and decide which risks should be addressed first. Consequently, the RADAR method may be more useful when detailed and precise ranking is required to optimize risk management processes.

Furthermore, applying the RADAR method can benefit due to its flexibility in weighting criteria. Unlike the RPN approach, which treats all factors (severity, occurrence, detection) equally, the RADAR method allows criteria to be weighted according to their relative importance in a specific context. It can result in rankings better aligned with the organization's needs and priorities.

This method can be particularly useful when different failure modes have similar ratings on certain criteria but differ significantly on others. The RADAR method makes it possible to distinguish these failure modes better and more accurately identify those that pose the greatest risk to the system.

### 4.2. Volume Sensitivity analysis

A sensitivity analysis of the obtained results is presented by comparing them with two MADM methods that fall under compromise (distance) methods – TOPSIS [38] and ARAS [19]. Additionally, a comparison was made with the results obtained using the RPN and RPN procedures with weighted criterion values (using multiplication). The sensitivity analysis method used is the procedure developed by Sałabun & Urbaniak [39]. This procedure is based on comparing the ranks of alternatives and is further explained:

$$WS = 1 - \sum_{i}^{I} 2^{-R_{x_i}} \cdot \frac{|R_{x_i} - R_{y_i}|}{max\{|1 - R_{x_i}|, |I - R_{x_i}|\}} \quad (11)$$

where: $I$ – total number of alternatives; $R_{x_i}$ and $R_{y_i}$ – average rank position for alternative $i$.

In Table 18, the ranking of alternatives is shown based on the application of the RADAR, TOPSIS, and ARAS methods, as well as the basic RPN procedure and the RPN procedure that considers the weights of the criteria.

According to Sałabun & Urbaniak [39], when the coefficient value is less than 0.234, it is considered that there is no similarity in the rankings. There is a similarity in the rankings in the range between 0.352 and 0.689, but the correlation is not significantly strong. In cases where the coefficient value exceeds 0.808, the similarity in rankings is considered absolute.

TOPSIS and ARAS provide identical rankings. Therefore, the WS coefficient is the same for both methods, i.e., 0.656. it indicates a similarity in rankings, but it is not absolute. The similarity is reflected in the lower part of the ranking list, approximately in the bottom 70% of alternatives. The most significant difference is observed among the top-ranked alternatives. One of the key characteristics of the RADAR method is demonstrated in this case. RADAR favors stability in the value of an alternative across all criteria, whereas TOPSIS and ARAS favor alternatives that perform well according to the most important criterion or have extremely high values according to one criterion.

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**Table 18.** Comparison of the rankings of alternatives determined by the application of different approaches

| | RADAR | TOPSIS | ARAS | RPN | Weighted RPN |
|---|---|---|---|---|---|
| $\boldsymbol{a = 1}$ | 17 | 17 | 17 | 12-13 | 12-13 |
| $\boldsymbol{a = 2}$ | 18 | 18 | 18 | 17 | 17 |
| $\boldsymbol{a = 3}$ | 12-14 | 5-7 | 5-7 | 14-16 | 14-16 |
| $\boldsymbol{a = 4}$ | 4-7 | 1-4 | 1-4 | 5-8 | 5-8 |
| $\boldsymbol{a = 5}$ | 4-7 | 1-4 | 1-4 | 5-8 | 5-8 |
| $\boldsymbol{a = 6}$ | 15 | 15 | 15 | 9 | 9 |
| $\boldsymbol{a = 7}$ | 1-2 | 11-12 | 11-12 | 1-2 | 1-2 |
| $\boldsymbol{a = 8}$ | 8-9 | 9-10 | 9-10 | 11-12 | 11-12 |
| $\boldsymbol{a = 9}$ | 21 | 21 | 21 | 18 | 18 |
| $\boldsymbol{a = 10}$ | 23-25 | 23-25 | 23-25 | 22-25 | 22-25 |
| $\boldsymbol{a = 11}$ | 23-25 | 23-25 | 23-25 | 22-25 | 22-25 |
| $\boldsymbol{a = 12}$ | 23-25 | 23-25 | 23-25 | 22-25 | 22-25 |
| $\boldsymbol{a = 13}$ | 12-14 | 5-7 | 5-7 | 14-16 | 14-16 |
| $\boldsymbol{a = 14}$ | 4-7 | 1-4 | 1-4 | 5-8 | 5-8 |
| $\boldsymbol{a = 15}$ | 4-7 | 1-4 | 1-4 | 5-8 | 5-8 |
| $\boldsymbol{a = 16}$ | 16 | 16 | 16 | 10 | 10 |
| $\boldsymbol{a = 17}$ | 1-2 | 11-12 | 11-12 | 1-2 | 1-2 |
| $\boldsymbol{a = 18}$ | 8-9 | 9-10 | 9-10 | 11-12 | 11-12 |
| $\boldsymbol{a = 19}$ | 3 | 8 | 8 | 3-4 | 3-4 |
| $\boldsymbol{a = 20}$ | 12-14 | 5-7 | 5-7 | 14-16 | 14-16 |
| $\boldsymbol{a = 21}$ | 11 | 13 | 13 | 12-13 | 12-13 |
| $\boldsymbol{a = 22}$ | 22 | 22 | 22 | 19 | 19 |
| $\boldsymbol{a = 23}$ | 19-20 | 19-20 | 19-20 | 20-21 | 20-21 |
| $\boldsymbol{a = 24}$ | 19-20 | 19-20 | 19-20 | 20-21 | 20-21 |
| $\boldsymbol{a = 25}$ | 10 | 14 | 14 | 3-4 | 3-4 |
| **WS** | / | **0.656** | **0.656** | **0.991** | **0.991** |

Compared with the classic RPN and weighted RPN parameters (when S, O, and D values are multiplied by their respective weights), the RADAR method yields a similar ranking. Therefore, it can be stated that the RADAR method is more suitable for FMEA problems than some other MADM methods.

### 4.3. Explanation of ranking deviation in relation to similar MADM approaches

In steps 2 and 3 of the method, the maximum proportion matrix α and the minimum proportion matrix β are formed, normalizing the values for each criterion. The formula used considers the relative distance of each alternative in relation to the maximum and minimum for a given criterion. In this way, the RADAR method does not directly favor extreme values (maximum or minimum) for any criterion. Still, it balances the alternative according to its proportional value relative to all criteria. This approach leads to a better ranking of alternatives that are more stable (i.e., those with less deviation across each criterion).

Most MADM methods (such as TOPSIS or ARAS) favor alternatives that achieve extreme values on the most important criteria, as these methods often rely on the maximization or minimization of specific values. For example, TOPSIS favors alternatives closest to the positive ideal solution (the best value) and farthest from the negative ideal solution.

RADAR, on the other hand, uses the relative relationship matrix (step 6), which considers the proportional relationships of α, β, and the empty ranges. It creates a balanced criterion that avoids favoring only extreme values and relies on proportional stability.

It is important to emphasize that there is no way to determine which method is better, nor can this be proven in any way. The choice of method depends on the nature of the problem being considered. Therefore, the RADAR method could be a useful tool for solving problems where the goal is to avoid the influence of an alternative with an extremely high value in one criterion compared to the others.

## 5. CONCLUSION

This paper introduces a new distance-based method, RADAR, primarily designed to rank alternatives according to specific criteria. The RADAR method operates on key principles that distinguish it from traditional approaches. It evaluates the distance of each alternative relative to the best and worst options for each criterion. It considers the range between these extremes to determine how much the alternatives vary.

An essential aspect of the RADAR method is its ability to factor in the relative importance of criteria, influencing the ranking outcome. The method is particularly effective in scenarios where alternatives are approximately equal; in such cases, it prioritizes alternatives that deviate the least and are not overly "poor" according to any criterion. Additionally, alternatives that exhibit "excellence" in specific criteria are ranked higher, depending on the criterion's importance.

One of the key advantages of the RADAR method is its simplicity and transparency in executing the steps, which makes it easy to apply in various decision-making scenarios. The method allows for a clear assessment of the differences between alternatives and their analysis within the given criteria without involving complex calculations. This approach ensures that the method can handle variations in criteria proportionally and reduces the impact of extreme values, thereby providing a more balanced and nuanced evaluation. Additionally, the RADAR method integrates different types of criteria effectively, combining them into a cohesive analysis while maintaining flexibility in its application. It makes the RADAR method accessible to practitioners who may not have advanced knowledge in multicriteria decision-making but can effectively apply the method to achieve accurate and reliable results.

One limitation of the RADAR method is its inability to handle zero values in the decision matrix, as division by zero renders the method's steps inapplicable. However, such situations are rare and generally negligible. Additionally, implementing RADAR can be complex, particularly in organizations accustomed to traditional methods. This complexity may lead to resistance from practitioners who are hesitant to adopt new frameworks, especially if unfamiliar with the underlying principles of multi-attribute decision-making.

Another challenge lies in comparing alternatives when the performance across criteria varies significantly. While RADAR emphasizes stability, this focus might overlook alternatives that excel in specific areas but perform poorly in others. It could lead to suboptimal decision-making in scenarios where exceptional performance in key criteria is critical. Lastly, prioritizing stability across criteria may inadvertently minimize the significance of outliers or extreme values, which could be crucial in certain contexts.

RADAR demonstrates its effectiveness when applied to the traditional FMEA approach by providing a refined ranking of failure modes, offering insights that the conventional RPN method might overlook. The comparison in this study shows that RADAR can yield similar or slightly different rankings compared to the traditional RPN approach, highlighting its stability and reliability in risk assessment contexts.

Future research will focus on enhancing the RADAR method by incorporating fuzzy sets theory and other related disciplines to refine the decision-making process further. The method's applicability to real-world problems across various domains will also be explored, ensuring its versatility and practical value. Specifically, further studies will address the limitations associated with zero values and investigate how RADAR can be adapted to handle more complex decision-making scenarios.

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